EXPLORING SPATIAL RISK: THE IMPACT OF VISIBILITY ON ICU MORTALITY

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EXPLORING SPATIAL RISK: THE IMPACT OF VISIBILITY ON ICU MORTALITY

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To my parents – your love and confidence never waivers.

To my husband – you struggled beside me, making this work possible.

To my three children – you cheered me on, as proud of me as I am each of you.

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SUMMARY

Optimal patient visibility in intensive care units has long been a significant design consideration but previous studies have lacked clear, quantified visibility metrics to support healthcare design or clarify the mechanisms of how visibility actually contributes to healthcare outcomes. In addition, previous studies examined proxy or process measures for outcomes rather than outcomes that are of direct interest to patients and clinicians. The purpose of this dissertation study is to systematically investigate the association between patient visibility and ICU mortality. Chapter 2 examines alternate visibility metrics and proposes a theoretical extension. Chapter 3 introduces and details the conceptual development of a new variable: isovist connectivity. Chapter 4 tests isovist connectivity meaning and significance against ICU patient mortality in a major teaching hospital. Consistent with previous studies, poorly visible and connected rooms were independently associated with higher ICU patient mortality. Furthermore, these rooms were not immediately apparent on examination of the plans, suggesting the need for robust spatial analysis to determine the presence of both patient visibility and visual access.

CHAPTER 1

INTRODUCTION

Optimal patient visibility from nursing locations has long been a significant design consideration for ICUs (Wedel, Warren, Harvey, Biel, & Dennis, 1995). Prior to two studies indicating a significant impact on ICU mortality (Leaf, Homel, & Factor, 2010; Lu, Ossmann, Leaf, & Factor, 2014), the relationship between patient visibility and patient-related outcomes was investigated by proxy variables such as waits for treatment, adverse events, or use of staff time. Studies focused on linear distances, barriers to interaction (doors), or staff distribution in the workspace. For example, chest pain patients located more than 25 feet from the physician work station or who had a door on their rooms were significantly more likely to wait more than 10 minutes for their initial physician assessment (K. Hall, Kyriacou, Handler, & Adams, 2008). Patients isolated for infection control were twice as likely to experience adverse events as their controls and significantly more likely to submit a complaint about their care, though there was no significant difference in hospital mortality (Stelfox, 2003).

Hendrich, Fay, & Sorrells (2004) postulated that decentralized nursing stations and “multiple observation points” were likely responsible for a decline in patient falls and improved safety. Nurses working in radial unit configurations spent more time at the bedside than their corridor configuration counterparts (Trites, Galbraith, Sturdavant, & Leckwart, 1970). Sturdavant (1960) found that increased visibility from nursing stations reduced travel distance and time for nurses. Nurses with more integrated patient assignments (how central the patient rooms are to the entire unit) made significantly more trips into their patient's rooms and nurse station (Hendrich et al., 2009). These studies suggested that inpatient unit design influences the process of care, providing insight into the underlying mechanism that links space to outcomes. But these studies did not empirically define spatial predictors in ways that allowed for floor plan comparison or study replication. Moreover, there was no direct tie to patient outcomes.

The purpose of this dissertation study is three-fold: (1) explore and critique existing visibility measures, (2) describe the development of a new visibility measure, Isovist Connectivity, and (3) test Isovist Connectivity against patient outcomes, namely, ICU patient mortality.

In Chapter 2 we expound upon and reexamine the Lu et al. (2014) results and through field of view (FOV) reanalysis, explore theoretical underpinnings and statistical test choice. We generally expect the same results given the same data set; rather, we hope to illustrate the potential for a dose-response relationship by means of ordinal grouping (low, medium, and high visibility). We first define and explain room visibility, patient head visibility, and distance variables as derived in Lu et al. (2014). Second, we redefine and reanalyze FOV. Last, we discuss all 4 variables as related to each other and ICU mortality.

In Chapter 3 we detail the historical framework and conceptual development of a new spatial variable – isovist connectivity (IC) - that combines both isovist and visibility graph theory to describe the socio-spatial exigencies of healthcare workers. The purpose of this chapter is three-fold. First, we introduce and discuss the isovist and visibility graph theory frameworks. Second, we relate isovist and visibility graph theories to behaviors in intensive care unit environments and discuss shortcomings. Finally, we detail the conceptual development and derivation of isovist connectivity (IC).

In Chapter 4, we classify ICU patient rooms using isovist connectivity and compare the resulting spatial values with mortality rates in sepsis patients. We foresee an inverse relationship between visibility affordances as quantified by IC and ICU mortality given previous research. The purpose of this chapter is to appraise IC robustness across various floorplan typologies (U-shaped, double-corridor, and triangular) and square footage, and to demonstrate relevance through rigorous analysis against a retrospectively collected patient data set.

Taken together, we account for the deficiencies in currently available visibility measures and introduce a new spatial variable to investigate the association between patient visibility and ICU mortality.

CHAPTER 2

PRELIMINARY STUDY

2.1 Abstract

Context: ICU mortality appeared to be related to architectural layout in two same-population case studies, for the sickest of patients. Such findings have significant implications for both ICU design and staffing, but existing metrics and methods of analysis require further refinement to determine the role of spatial layout in ICU mortality.

Objective: To explore existing architectural layout metrics and methods of analysis using previously reported data.

Design: Secondary data analysis/cohort study.

Setting: A single medical ICU (MICU) at Columbia University Medical Center.

Patients and Architecture: We reanalyzed hospital discharge data for all patients (N=664) admitted to the MICU from Jan.1, 2008 – Dec.31, 2008. We obtained architectural floor plans and information about the physical characteristics of the MICU as well as information about staffing and admission patterns from Leaf et al. (2010) and from direct personal communication with Dr. Leaf. We also reanalyzed architectural layout metrics obtained from Lu et al. (2014).

Main Outcome Measure: ICU mortality.

Results: For the 114 patients with an Acute Physiology and Chronic Health Evaluation II (APACHE II) score >30, ICU mortality was significantly, ordinally related to level of visibility group: low visibility room mortality = 67%; medium visibility room mortality = 49%; and high visibility room mortality was 36%, p=0.013.

Conclusion: The increasing rates of survival from low-to-high visibility categories of rooms was expected given the significant categorical relationship in Leaf et al. (2010) and linear relationship in Lu, et al. (2014). Visibility analysis by group suggests a dose-response relationship, but further investigation is required with other patient types, in other settings and institutions, and with improved metrics to make patient care and unit design recommendations.

2.2 Background & Objectives

Optimal patient visibility from nursing locations has long been a significant design consideration for ICUs (Wedel et al., 1995). Prior to 2010 however, no evidence existed supporting a relationship between patient visibility and clinical outcomes; the relationship was investigated by proxy variable or inferred. In a finding that was nothing short of groundbreaking for those who study and design healthcare spaces, Leaf and colleagues (Leaf et al., 2010) reported that severely ill patients [those with an Acute Physiology and Chronic Health Evaluation II (APACHE II) > 30] who were admitted to low-visibility rooms (rooms where no part of the patient could be seen from the central nurse station) experienced significantly higher ICU mortality than those admitted to high-visibility rooms, (those where patients could be seen from the central nurse station), 66.7% and 46.7% respectively; p = 0.042. This was a 12 bed ICU where the rooms were arranged around the nurse station (a "racetrack" typology).

This methodology is similar to that used by Catrambone and colleagues, in an effort to both operationalize and benchmark desirable unit characteristics as deemed by Agency for Healthcare Research and Quality (2007). The authors measured '"Visibility" of patients from nurse work areas', by standing at each nurse charting area (station) and counting the number of beds where the upper third of the patient could be visualized when the door or room blinds were open (Catrambone, Johnson, Mion, & Minnick, 2009). The nurse charting station was defined as 'the place where nursing staff charted data beyond what was recorded on flow sheets'. It would be difficult, however, to extend this methodology to other floor plan typologies, for example, distributed nurse stations, where every patient is ostensibly directly viewed. While self-explanatory and enumerating, the Leaf et al. (2010) and Catrambone et al. (2009) assessment methods cannot be executed prior to construction completion, are labor intensive, and crucially, tend towards the subjective, e.g. did the observer lean or strain to gain a more advantageous view and were observations truly taken from every available point in the nurse station.

Given the constraints detailed above, Lu and colleagues (2014) conducted a conceptual replication of 'Relationship Between ICU Design and Mortality' (Leaf et al., 2010). The primary goal of the replication study was to rigorously define and give significance to both established and new visibility metrics. The authors reported a significant linear relationship between field of view[1] (FOV) to the nurse station and ICU mortality, accounting for 33.5% of the variance in ICU mortality for patients with an APACHE II >30 ($p=0.049$) (Lu, Ossmann, Leaf, & Factor, 2014), **Figure 2.1**. However, some findings were contrary to expectations. In particular,

[1] Defined in Lu, et al. (2014) as the maximum viewing angle from the patient's head to the rest of the unit, which may include hallways, the central nursing station, etc.

while FOV correlated with three other spatial variables - the visibility of the head of the bed from the nurses' station, the visibility of the patient room from the nurses' station, and distance from the nurses station - only FOV was significantly related to ICU mortality, **Table 2.1.**

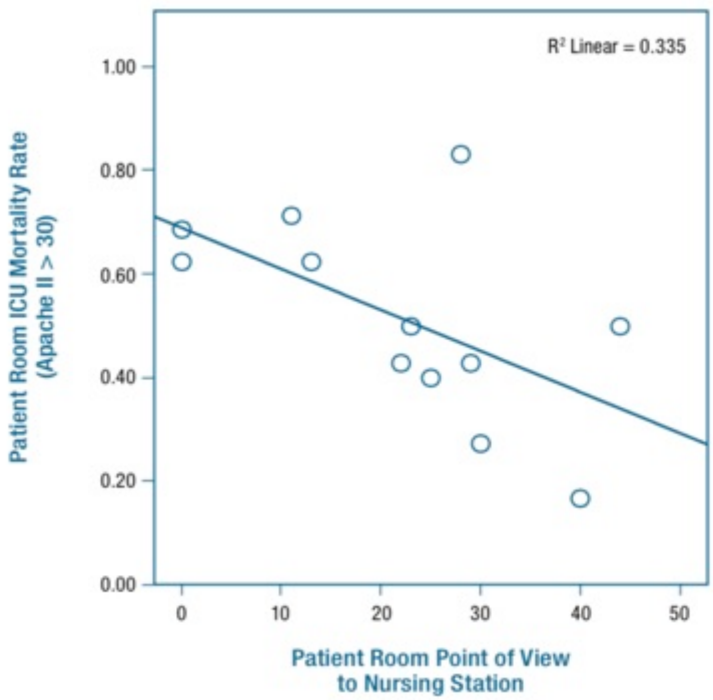


Figure 2.1 The field of view from the patient head to the central nursing station explained 33.5% of the variance in ICU mortality (p=0.049) by room for patients with the greatest severity of illness (APACHE II > 30). Reprinted with permission.

The reanalysis by Lu and colleagues (2014) provided a most compelling case for the built environment-outcomes relationship, however like all studies, encountered limitations. Although meeting the assumptions of independence and homoscedasticity, we question adherence to linearity, i.e. a constant rate of change (ICU mortality) over the range of the independent variable (FOV). For example, will a 4° visibility increase (as found between Rooms 24 and 36) provide a corresponding linear decrease in the mortality rate? We also wish to probe into the high correlation between FOV and other visibility measures and lack of significance.

Table 2.1 Visibility Measure Correlation Matrix**.** Field of view is positively correlated with patient head visibility, room visibility, and inversely correlated with distance in the 12-room MICU sample.

	FOV to CS	Distance (bed to CS)	Head visibility	Room visibility
FOV to CS				
Distance (bed to CS)	-0.852**			
Head visibility	0.691*	-0.430		
Room visibility	0.891**	-0.727**	0.861**	

*p<0.05
**p<0.01

The purpose of this chapter is to reexamine the Lu et al. (2014) results and through FOV reanalysis, explore theoretical underpinnings and statistical test choice. We expect similar results given the same data set; rather, we hope to illustrate the potential for a dose-response relationship by means of ordinal grouping (low, medium, and high visibility) versus a continuous relationship. We first define and explain room visibility, patient head visibility, and distance variables as derived in Lu et al. (2014); we then redefine and reanalyze FOV; last, we discuss all 4 variables as related to each other and ICU mortality.

2.3 Variable Definitions

2.3.1 Room Visibility

By this method, Lu and colleagues first overlaid a grid of vantage points in 1 ft^2 upon the layout broken only by visual barriers using Depthmap (Turner, 1998). The average visibility value for all locations in the room was calculated as the percentage of points within the central nursing station that could "see" that point, **Figure 2.2a.** The average value of all points (in %) resulted in a room visibility score (%). With this measure, Lu et al. (2014) sought to account for visibility to all spaces in the patient room, including the bed.

2a. Room Visibility **2b. TVi/Patient Head Visibility** **2c. FOV/Walking Distance**

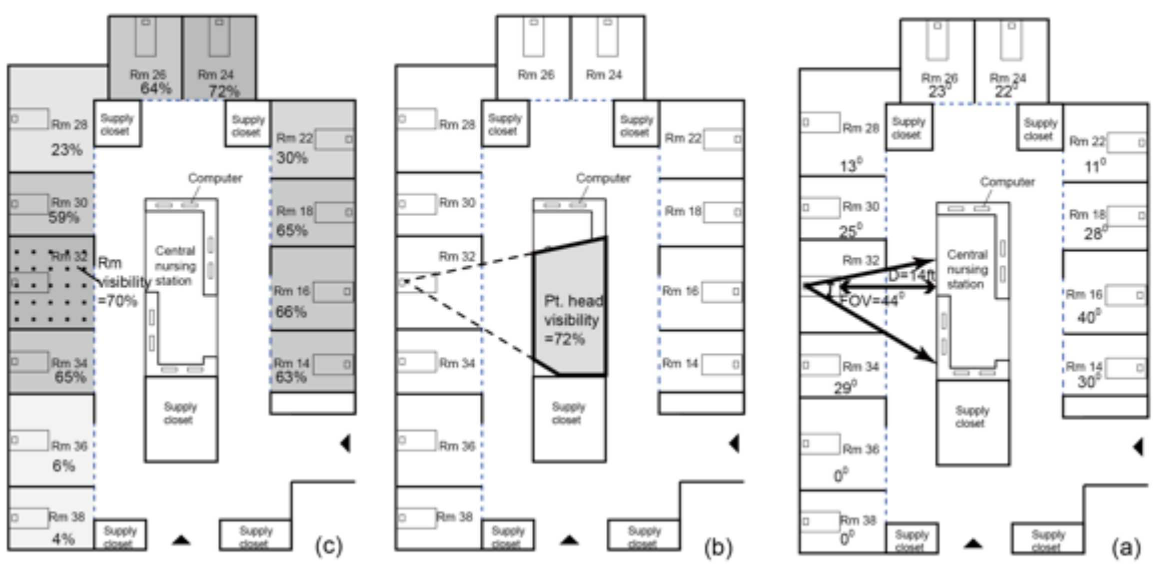


Figure 2.2. (a) Patient Room Visibility (%), (b) Patient Head Visibility (Targeted Visibility or TVi)(%), and (c) Field of View (FOV) (°), from the patient head and shortest Walking Distance (ft.). From Lu, et al. (2014), with permission.

2.3.2 Patient Head Visibility as measured by Targeted Visibility (TVi)

Targeted visibility (TVi) is a 2-D technique in Depthmap (Turner, 1998) that quantifies the visibility of a pre-specified set of visual features in the physical environment, such as the number of visible patient beds in a nursing unit from any location (Lu, 2010). As with room visibility, calculating patient head visibility from the central nurse station began with an overlaid grid of vantage points in 1 ft^2 upon the layout broken only by visual barriers, **Figure 2.2a**. Dr. Lu then calculated the number of points within the nursing station from which the patient head could be seen, **Figure 2.2b.** Patient head visibility was defined as the ratio of visible points to total points, approximating the percentage of area within the nursing station that could see a patient head.

2.3.3 Walking Distance between the Nurse Station and Patient Rooms

Walking distance, defined as the shortest distance from the bottom part of patient bed to central nursing station was calculated in feet using AutoCAD, **Figure 2.2c**.

2.4 Methods

2.4.1 Setting and Characteristics

A detailed description of the setting, staffing, and unit characteristics is found in Lu et al. (2014). In summary, the medical intensive care unit (MICU) at Columbia University Medical center accepted patients directly from all admission channels and assigned beds randomly. Board-certified intensivists and residents staffed the unit. Nurses worked 12-hour shifts with a typical ratio of 1:2. Per nurse, ratios rose to 1:3 for approximately 90 minutes per 12-hour shift. Telemetry monitoring was displayed on two monitors in the nurse station, on the wall adjacent to the supply closet.

The MICU had a racetrack typology, **Figure 2.2;** the12 patient rooms were non-uniform surrounding a central nurse station. Computer charting was available at the central nurse station, bedside or with the use of 2 computers-on-wheels.

2.4.2 Outcome Measurements

The outcome of interest was ICU mortality, (defined as death occurring in the ICU).

2.4.3 Primary Exposure Variable

2.4.3.1 Field of View

Upon revisiting the original spatial analysis for Lu et al. (2014), we found that FOV was not defined as calculated in the published paper, which described FOV as the 'maximum viewing angle from the patient's head to *the rest of the unit*, which may include hallways, the central nursing station, etc.'. This cannot be, as having zero degrees of visibility to the rest of the unit (Rooms 36 and 38) can only mean that the door is perpetually closed. Upon examination of the original drawings, FOV was actually calculated as 'the maximum viewing angle from the patient's head *to the central nurse station only*'; we retain the original calculation and define FOV to the nurse station as 'the maximum viewing angle from the patient's head to the central nurse station only', **Figures 2.2c and 2.3**. Field of View is reported in degrees.

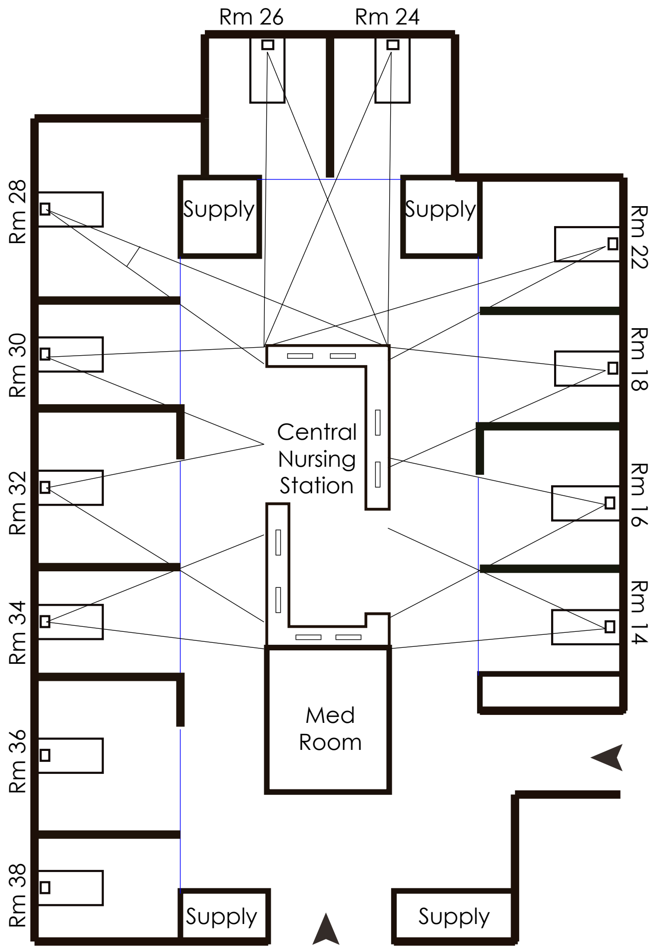


Figure 2.3 Field of View to the Nurse Station, from which FOV was calculated in Lu, et al. (2014). Note that Rooms 36 and 38 have a FOV score of 0; these rooms have no visibility to the central nurse station. Leaf et al. (2010) also reported that Rooms 22 and 28 had no visibility to the nurse station, highlighting the significance of bed position within each room.

2.4.3.2 Field of View Groups

The logic for the groups follows FOV trends, **Figures 2.4 and 2.5.** Low Visibility: Rooms 38, 36, 28, and 22 were the lowest by FOV scores and patients in those rooms were also deemed invisible from the nurse station in Leaf, et al. (2010). Medium Visibility: Rooms 34, 30, 26, 24, 18 and 14. High Visibility: Rooms 32 and 16 clearly had the highest FOV.

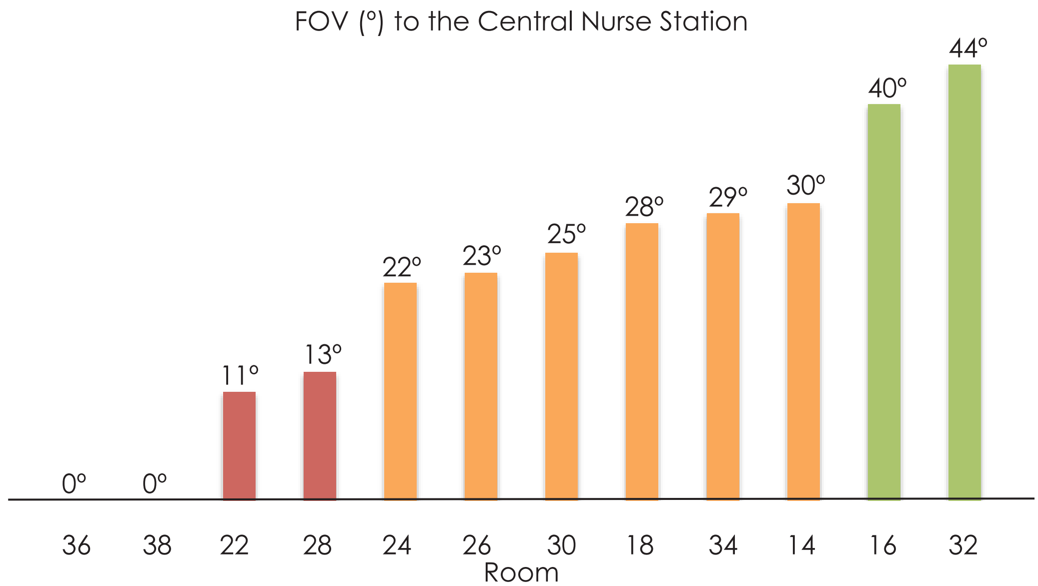


Figure 2.4 FOV by visibility groups; Red = Low (including 0 rooms), Orange = Medium, Green = High.

2.4.4 Covariates

We examined age, gender, admission diagnosis, and used APACHE II scores as acute illness severity metrics. APACHE II scores were calculated by the MICU critical care fellows and were obtained directly from Dr. Leaf.

2.4.5 Statistical Analysis

Field of view values are reported as raw scores by patient room; rooms are categorized as Low, Medium, or High Visibility. All categorical variables are reported as counts with percentages. Skewed continuous variables, as determined by the Shapiro-Wilk test, are reported as median and interquartile range (25-75 percentiles). Unadjusted comparisons of descriptive variables and outcomes were calculated using Pearson correlation (categorical) or Kruskal-Wallis test (non-normal), with $p \leq 0.05$ considered significant. We used the

Cochran-Armitage Trend (Armitage, 1955; Cochran, 1954) test for dose-response for the ICU mortality analysis, as a test of the association between categorical variables: a variable with 2 categories (lived vs. died) and a variable with *k* categories (Low, Medium, & High Visibility). We report Z scores with $p \leq 0.05$ considered significant.

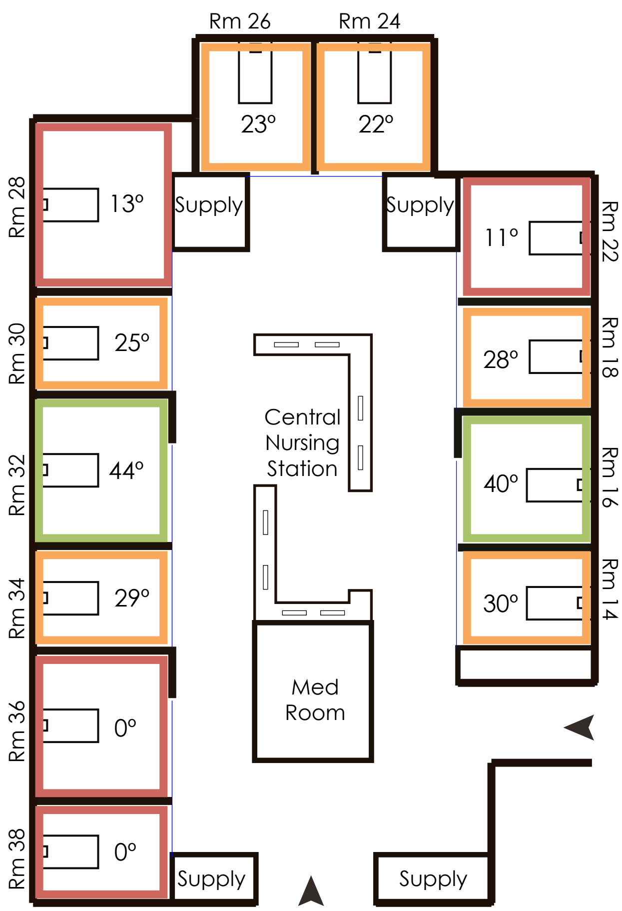


Figure 2.5 Floor plan with FOV Visibility Groups overlaid: Red = Low, Yellow = Medium, and Green = High.

2.5 Results

2.5.1 Patient Characteristics and Outcome Metrics

2.5.1.1 Full Set

A total of 664 patients were included in the full set (all acuity levels). Across the entire sample, there was no significant difference between visibility groups for age, gender, APACHE II score, or admission diagnosis, **Table 2.2.** There was no significant difference in ICU mortality between visibility groups for the full set, **Table 2.3.**

2.5.1.2 APACHE II > 30 Subset

A total 114 patients were included in the APACHE II > 30 subset. There was no significant difference between visibility groups for age, gender, or admission diagnosis, **Table 2.4.** The distribution of subjects by visibility group, low to medium to high was 39, 61, and 14, respectively. ICU mortality varied significantly by level of visibility group (Cochran-Armitage Trend Test Z=2.22; p= 0.013); ICU mortality for the low, medium, and high visibility groups were 67%, 49%, and 36%, respectively **Table 2.5.**

2.6 Discussion

2.6.1 ICU Mortality by FOV Group

We expected a decreasing mortality trend for the sickest of patients from low to high visibility category rooms (as measured by FOV) given the significant linear relationship detailed earlier in this chapter (Lu, et al., 2014). Field of view is strictly

Table 2.2 Full Sample Baseline Demographics and Admission Diagnoses by visibility groups. Patient characteristics across visibility groups are not significantly different. The number of rooms per visibility group are: Low Vis = 4,Med Vis =6, High Vis =2.

Full Sample Characteristics	Overall N=664	LOW VIS n=222	MED VIS n=337	HIGH VIS n=105	p Value
Demographics					
Age, y, median, [IQR]	61 (48-73)	60.5 (46-73.3)	62 (49-74)	62 (45.5-72)	0.62
Female, %	47.4	47.3	48.4	44.8	0.81
Admission Diagnosis, No. (%)					
Sepsis/Septic Shock	163 (24.6)	57 (25.7)	87 (25.8)	19 (18.1)	
Cardiac	48 (7.2)	10 (4.5)	30 (8.9)	8 (7.6)	
Gastrointestinal Bleed	141 (21.2)	50 (22.5)	68 (20.2)	23 (21.9)	
Neurologic	30 (4.5)	15 (6.8)	12 (3.6)	3 (2.9)	
Respiratory Failure	218 (32.8)	71 (32.0)	105 (31.2)	42 (40.0)	
Other	64 (9.6)	19 (8.6)	35 (10.4)	10 (9.5)	0.26
Severity of Illness					
APACHE II, median [IQR]	20.0 [14.0-27.0]	20.0 [14.0-27.0]	20.0 [13.0-28.0]	18.0 [11.5-27.0]	0.34

APACHE = Acute Physiology And Chronic Health Evaluation; IQR = interquartile range, 25 and 75%.

Table 2.3 Unadjusted Outcome

Full Sample Outcomes	Overall N=664	LOW VIS n=222	MED VIS n=337	HIGH VIS n=105	p Value
ICU mortality (%)	131/664 (19.7)	46/222 (20.7)	70/337 (20.8)	15/105 (14.3)	0.13

Table 2.4 High Acuity Subgroup Baseline Demographics by visibility groups. Patient characteristics across visibility groups are not significantly different. The number of rooms per visibility group are: Low Vis =4, Med Vis =6, High Vis =2.

APACHE II >30 Subgroup Characteristics	Overall N=114	LOW VIS n=39	MED VIS n=61	HIGH VIS n=14	p Value
Demographics					
Age, y, median [IQR]	68 (55.5-76.5)	65 (51-76)	71 (60.5-77.8)	65 (54-79.5)	0.14
Female, %	46.5	39.5	48.5	55.6	0.46
Admission Diagnosis, No. (%)					0.52
Sepsis/Septic Shock	48 (42.1)	16 (41.0)	27 (44.3)	5 (35.7)	
Cardiac	18 (15.8)	5 (12.8)	10 (16.4)	3 (21.4)	
Gastrointestinal Bleed/Liver Failure	11 (9.6)	5 (12.8)	6 (9.8)	0 (0.0)	
Neurologic	2 (1.8)	2 (5.1)	0 (0.0)	0 (0.0)	
Respiratory Failure	29 (25.4)	10 (25.6)	15 (24.6)	4 (28.6)	
Other	6 (5.3)	1 (2.6)	3 (4.9)	2 (14.3)	
Severity of Illness					
APACHE II, median [IQR]	34.0 [32.0-38.0]	35.0 [32.0-38.0]	34.0 [32.0-38.8]	34.5 [30.8-37.0]	0.40

APACHE = Acute Physiology And Chronic Health Evaluation; IQR = interquartile range, 25 and 75%.

Table 2.5 High Acuity Subgroup Outcome. ICU mortality inversely related to visibility for the sickest of patients.

APACHE II >30 Subgroup Outcomes	Overall N=114	LOW VIS n=39	MED VIS n=61	HIGH VIS n=14
ICU mortality n (%)	61 (53.5)	26 (66.7)	30 (49.2)	5 (35.7)
Cochran Armitage Trend Test				
Asymptotic Test	**Z** 2.217124	**p** 0.013*		

a metric, and as such can be applied in numerous permutations, altering the origin or area of interest. Given this flexibility, however, we must take care to match operational and conceptual definitions. Lu and colleagues focused on the central nurse station but in so doing *also captured the space before and beyond the nurse station*. Like all rooms in the study setting, Rooms 36 and 38 (ascribed FOV 0°) certainly enjoyed a view to the hallway; furthermore, the FOV for Rooms 14, 18, 22, 30, and 34 would expand if taken to the door openings, **Figure 2.6**. View is not artificially restricted to an arc narrower than the afforded opening, in this case, the doorway. Notably, it does appear that Rooms 36 and 38 are among the poorest given their orientation in the plan, e.g. directly facing a corridor wall and farthest from the central station, a fortunate happenstance that somewhat preserves the FOV findings.

However, FOV interpretation is therefore confounded – it is a question of mechanism. We cannot know the influence of the corridor, nor can we ignore the potential confluence of configuration. There may be differential outcomes for patients assigned to rooms with no view to the nurse station; there may also be additional missing variables, e.g. the quality of the space external to the nurse station. The impact of the corridor is not insignificant, and indeed forms the basis of layout studies in other building types: layout determines visibility of space, which in return affects communication and interaction in office and museum settings (Choi, 1999; Peponis et al., 2007; Peponis, Dalton, Wineman, & Dalton, 2004; Rashid, Kamschroer, Wineman, & Zimring, 2006; Wineman & Peponis, 2009);

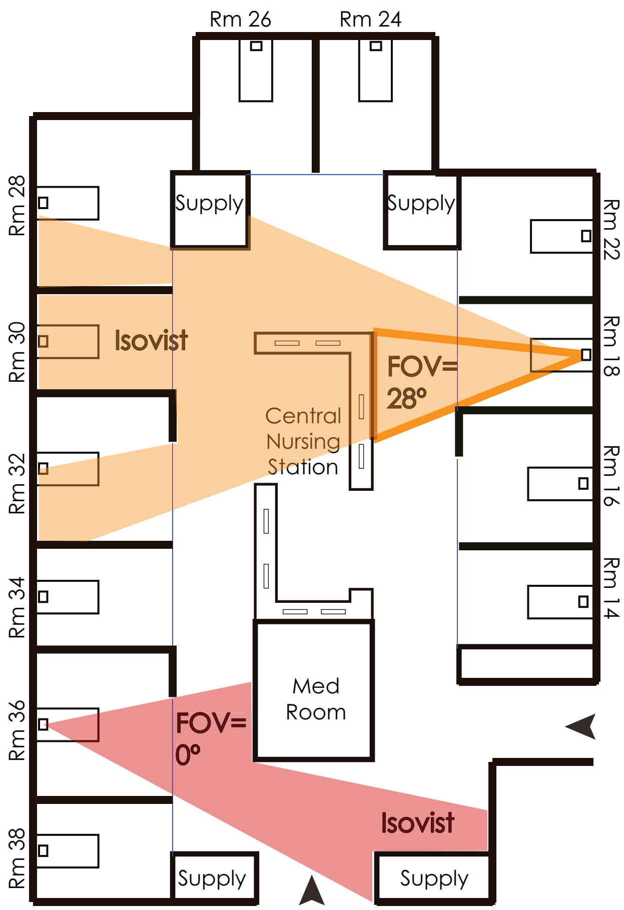


Figure 2.6. Example of Field of View to the Nurse Station (Lu, et al., 2014) shown as an orange triangle, overlaid with actual view (the isovist), shown in orange shading. Note that actual FOV extends well beyond the nurse station and that Rooms 36 (shaded in red), for example, has views to the corridor. All central nurse station surfaces are at desk height.

and people are more likely to interact in an area where they can see and be seen by others (Penn, Desyllas, & Vaughn, 1997). We also question the central nurse station focus, both from a unit design (decentralized stations/no central station) and behavioral perspective.

We conclude that the FOV 'to the nurse station only' metric requires additional refinement: (1) how to differentiate between the nurse station area and the space before and beyond and (2) how to attribute visibility areas to those rooms not afforded direct purview to the nurse station. Future study should also examine variability by configuration.

Precision of mechanism aside however, there appears to be a relationship between visibility to the central nurse station, including the space before and beyond, and ICU patient mortality for the sickest of patients. This categorical analysis proposes that there may be no conferred advantage at 'medium visibility levels', a suggestion that was obscured in the linear analysis, **Figure 2.1** and **Table 2.5**. It is logical to suppose that a moderate amount of visibility is merely sufficient, the built environment a benign backdrop to patient care activities. Mortality trends at the extremes of visibility affordances, however, give pause. From a clinical perspective, it resonates that a patient 'on display' is experienced differently than a patient in a back hall corner. However clinician bias confirming, further investigation is required with other patient types, in other settings and institutions, and with improved metrics, to make patient care and unit design recommendations. With a much-expanded sample, it may also be possible to explore the precise limits around visibility, providing designers with a range of acceptability.

2.6.2 Additional Visibility Metrics – Room Visibility, Patient Head Visibility, and Walking Distance

2.6.2.1 Room Visibility and Field of View

Lu and colleagues reported a significant correlation between room visibility from the central nurse station and FOV, Patient Head Visibility, and Distance (negative). Again this is logical; the bed resides within the room and more distant rooms are less likely seen. Room visibility was not, however, related significantly to ICU mortality. Visibility to the entire room likely reflects the ability to see the patient, staff, families, and equipment, but may also imply unrealized patient safety value. An additional view to the sink, for example, may allow for hand washing verification, but not provide direct information about the patient. Bed primacy may be a peculiarity of ICUs, where patients tend to remain stationary (as opposed to a general care floor). Future study may consider examining room visibility for questions related to family involvement or sense of privacy.

2.6.2.2 Patient Head Visibility (TVi) and Field of View

Patient head visibility, as measured with TVi was not significantly related to mortality rates in Lu et al. (2014), likely related to the sample unit morphology. It appears that the TVi score may have been inflated due to the nursing station shape – long and narrow – implying significant but unrealized, visibility gains, **Figure 2.7.** Rooms 24 and 26 face the nurse station lengthwise, giving an elongated but narrow field from which to target the patient head; patient heads are approximately 40 feet from the center of the nurse station, but the TVi metric includes areas of the nurse station that are at 51 feet. Furthermore, half of the workstations available in the volume attributed to Rooms 24 and 26 appear to be directionally opposite from the HOBs and would not be peripherally visible. In short, the additional nursing station volume and orientation may be too distant and directionally dependent to meaningfully allow surveillance.

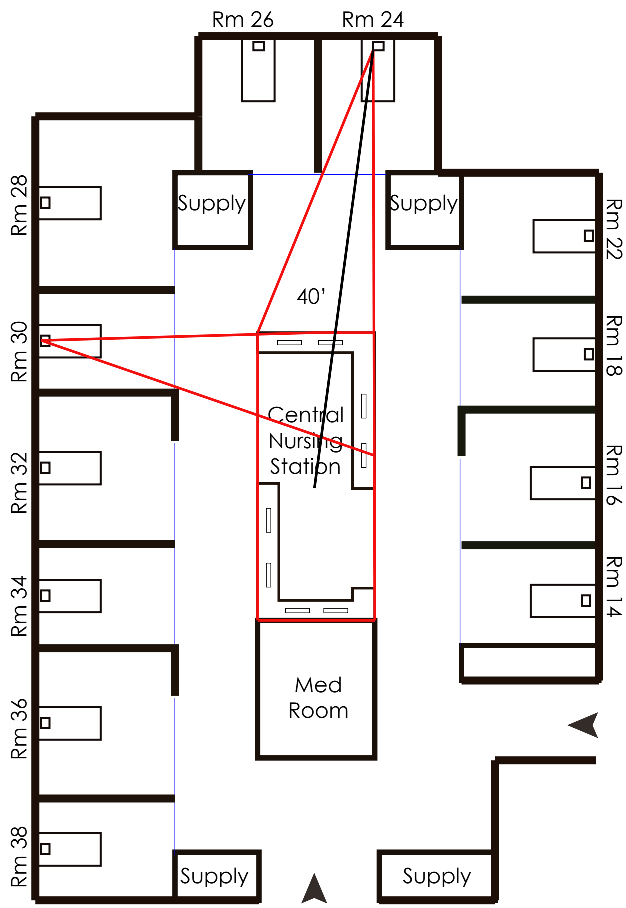


Figure 2.7 TVi fields from the HOB. Note that locations in the central station beyond 40 feet are considered available to the HOB in Rooms 24 and 26.

Lu and colleagues (2014) also reported that patient head visibility (TVi) positively correlated with FOV [$R^2 = 0.691$, $p = 0.013$], **Table 2.1.** Upon closer inspection, we noted two outliers – Rooms 24 and 26, **Figure 2.8**; it appears that patient head visibility as calculated with TVi may have correlated with ICU mortality had there been a distance limit. The 'inflated' TVi scores likely commanded an expected 'lowest mortality rate' for those rooms; as a result, patient head visibility as measured by TVi did not predict mortality.

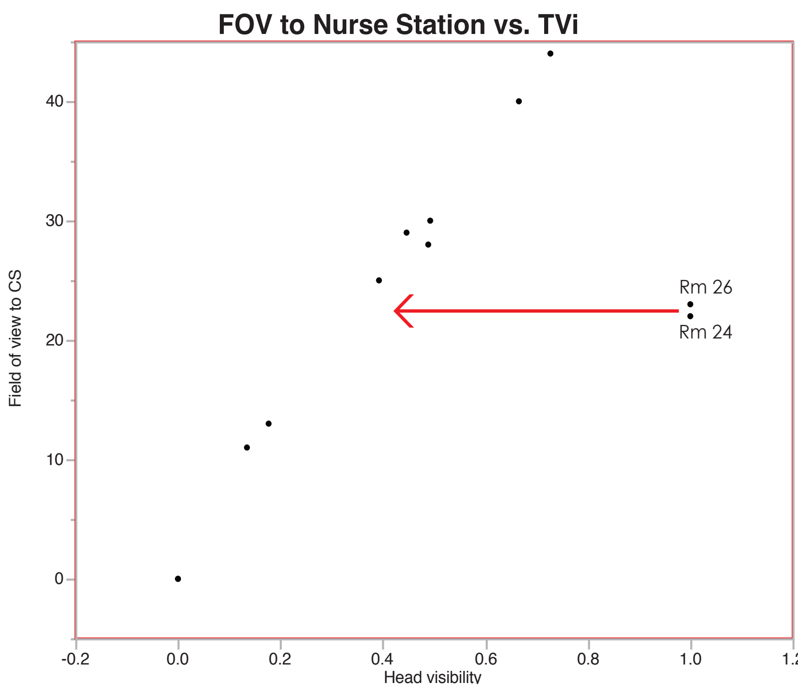


Figure 2.8. Scatterplot of FOV by TVi, [$r(10) = 0.691$, $p = 0.013$]. Rooms 24 and 26 are outliers, showing the likely effects of elongated nurse station views and lack of distance control. FOV appears to be more robust to distance and spatial form.

As mentioned previously, we also question central nurse station selection as the primary surveillance space. Granted, this choice has precedent; Leaf and colleagues (2010) used the nursing station as a point of reference for their study as did Catrambone (2009). All three authors assume central station primacy, and may have missed the surveillance activities possible from corridors and other patient rooms – namely, concurrent visibility (Peponis et al., 2004). As noted with FOV, a nurse standing in the corridor – in line between the central station 'point' and the patient head could also potentially see that patient. Future studies may wish to examine views to the patient head from other areas in the unit.

Patient head visibility as measured by TVi is certainly worthy of further refinement, but is not a useful spatial metric in its current form, as it does not discriminate across distance or spatial form, and is not robust to the functional program, in this case, workstation direction. Like FOV, patient head visibility as measured by TVi also inadvertently reflects visibility from the corridor, if within sight lines.

2.6.2.3 Walking Distance and Field of View

Walking distance, defined in Lu et al. (2014) as the shortest distance between the foot of the patient bed and the nurse station, would also benefit from additional refinement; distance can be operationalized numerous ways, e.g. we are unclear as to when the nurse station was 'reached'. For example, does our interest lie in how far nurses must walk before they can reasonably converse with or see those in the nurse station, physically reach the actual entrance into the station, or simply touch the edge of the desk? Unless we are concerned with a physical intervention, preventing self-extubation for example, distance may be a proxy measure for being close enough to participate or be aware of needed action. Several studies show a relationship between distance and time at the bedside, actual patient observation, and/or response times. Patients were seen sooner when placed in a room without a door and closer to the physician workstations (K. Hall et al., 2008) and nurses visited their patients more frequently when their room assignments were more integrated (how central the patient rooms are to the entire unit), which of course is not necessarily related to distance (Hendrich et al., 2009; Heo, Choudhary, Bafna, Hendrich, & Chow, 2009).

Lu and colleagues (2014) reported that distance and FOV were highly negatively correlated, **Table 2.1,** and yet distance was not associated with ICU mortality for the sample. We see 2 potential explanations: (1) the correlation was due to extreme FOV scores, **Figure 2.9** and (2) distance operationalization as previously described. Distance influences both sensorial awareness and physical action, but the distance requirement for each may be very different. Additional measurement and definition refinement would improve the theoretical model and results interpretation.

2.7 Conclusion

In this paper we demonstrated (1) an inverse trend between visibility and ICU mortality for the sickest of patients and (2) the potential for no effect at a medium visibility level. We also identified areas for refinement and improvement in currently available visibility metrics and methods, some of which will be easier

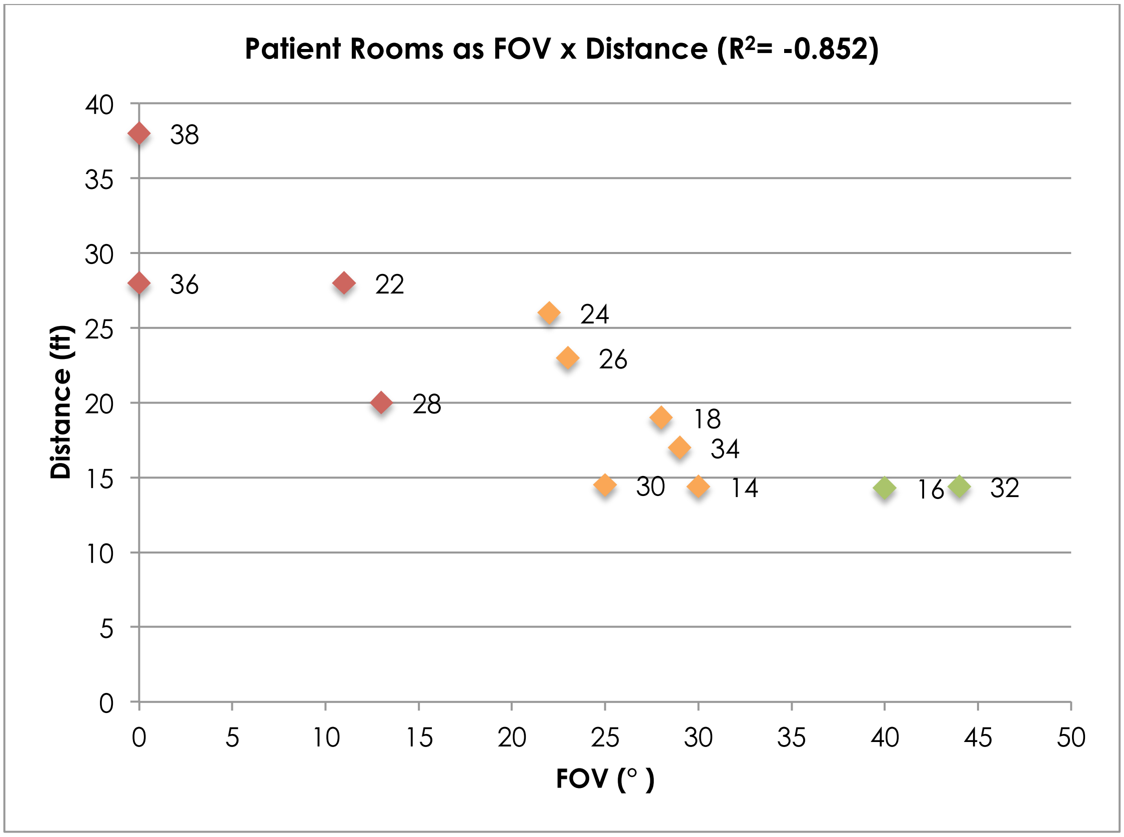


Figure 2.9 Field of View by Distance (Red= Low; Medium= Orange; Green= High); Rooms 24 and 26 are in the Medium group by FOV, but in terms of distance, are most similar to the lowest FOV group. This may account for the non-significant relationship between distance and ICU mortality.

to remedy than others. Future visibility metrics and methods should (a) account for all potentially worker-occupied space, (b) account for patient head of bed primacy, (c) be robust across configurations, and (d) be robust to distance. We remain convinced that there are ranges of visibility affordances, as suggested by the 'no effect' medium group. Finding the thresholds will require study across numerous settings, institutions, and patient types. Before, however, we define visibility thresholds, we must agree upon visibility metrics.

CHAPTER 3

ISOVIST CONNECTIVITY: MEANING AND SIGNIFICANCE

3.1 Abstract

The interrelationship between occupation and movement spaces as affected by configuration and topology are well described (Hillier, 2007), and indeed project into the co-presence and co-awareness necessary for patient care delivery. This generic description fails, however, in institutional environments, e.g. hospitals, prisons, and inpatient psychiatric wards, whereby workers must maintain surveillance of specific occupied space, regardless of the configuration. This paper details the conceptual framework and development of a new spatial variable, isovist connectivity, that combines both isovist and visibility graph theory to describe the needs of healthcare workers. As compared with the original definition of the isovist, isovist connectivity is concerned with the set of points that can see the vantage point, rather than set of points visible from the target. We propose that isovist connectivity (IC) reflects the potential for concurrent patient surveillance and organizational awareness.

3.2 Introduction

Experience and superstition teach the significance of 'rooms in front of the nurse station'. Indeed, the latest Society of Critical Care Medicine (SCCM) design guidelines[2] reinforce the value of direct visualization, stating that “each patient’s face and body position should be easily seen from the main ICU corridor” (p.1591) or from the nurse or team station (Thompson et al., 2012). In addition to the newly recognized importance of the main corridor, the 2012 update accounts for decentralized unit designs, suggesting a clear view of patients from decentralized work areas and from more than one station if possible. This guideline is profoundly architectural, seemingly prescriptive, and yet so general as to preclude measurement (‘easily seen’ and ‘clear view’) and thereby, visualization attainment. The generalities in the guidelines reflect the lack of validated visibility metrics as well as the variability found in ICU design.

Patient rooms and support area configurations vary widely, taking on generic forms or typologies that can be described as spoke or cruciform, parallel corridor or racetrack, off bed, surrounded or radial, or U-shaped configurations (James & Tatton-Brown, 1986). Seeking to gain a sense of typology choice, Rashid (2006) examined the 19 ICUs built between 1993 and 2003 that were awarded an ICU design award from the SCCM, the American Academy of Critical Care Nurses, and the American Institute of Architects. This inquiry found 7 different nurse station configurations among 4 differing unit layout typologies; the most common (12 of 19) was racetrack. Additionally, there was variation in the number of patient rooms per unit, support service area locations, and unit entrances. Catrambone et al. (2009) searched for the various design

[2] Until 2012, designers and hospitals were operating under the 1995 SCCM design guidelines, which stated that all patients must be situated so as to allow direct (or indirect, e.g. video) visualization at all times, preferably with a direct line of site to the nurse station (Wedel et al., 1995).

characteristics deemed desirable by the Agency for Healthcare Research and Quality (AHRQ) 2007 initiative, "Transforming Hospitals: Designing for Safety and Quality". Among other measures, Catrambone and colleagues examined 'patient visibility' in 56 randomly selected metropolitan hospital ICUs and medical surgical units. Across 8 different ICU design typologies, only 63.4% (SD 31.2) of the top 1/3 of patient beds were seen when standing up at a nurse charting station, and no typology, layout, number of rooms, or combination of support areas was superior in visibility.

Design guidelines exist for a primary purpose – the safety and benefit of patients. However, currently available metrics do not allow designers and clinicians to verify if visibility recommendations are met, nor is there any possibility of empiric comparison across floor plans. Furthermore, visibility as described in the SCCM guidelines does not address visual access for the clinician, (e.g. awareness of co-workers), which we suggest is an essential component of team-based care (Heerwagen, Kampschroer, Powell, & Loftness, 2004; Rashid, 2009) and which may in turn, affect patient safety.

This chapter details the historical framework and conceptual development of a new spatial variable – isovist connectivity (IC) - that combines both isovist and visibility graph theory to describe the socio-spatial needs of healthcare workers. The purpose of this chapter is three-fold. First, we introduce and discuss the isovist and visibility graph theory frameworks. Second, we relate isovist and visibility graph theories to behaviors in intensive care unit environments and discusses shortcomings. Finally, we detail the conceptual development and derivation of isovist connectivity.

3.3 Visibility Measures – Theoretical History and Framework

Historically studied building types (e.g. museums, university commons, offices, and factories) range broadly in configuration, topology, purview, and program. These elements form the basis for a deep body of work describing the interrelationship between spatial occupation, unplanned encounters, and movement across space (Choi, 1999; Hillier, 2007; Peponis et al., 2004), as measured by isovist and visibility graph measures. A generic description across building type is necessary; theory and measurement that is only particularly applicable has little utility and contradicts principles of man and environment studies (Proshansky, Ittelson, & Rivlin, 1970). We suggest however, that 'extremely programmed' institutional environments, e.g. hospitals, prisons, and inpatient psychiatric wards may overwhelm generic occupational principles and metrics, whereby the workers must maintain surveillance of specific occupied space *and* general visual access (Archea, 1977) (co-awareness and co-presence) - configuration, topology, or purview notwithstanding.

3.3.1 The Isovist Defined

Grounded in visual perception theory (Gibson, 1986) and built upon the work of Tandy (1967), Benedikt (1979) attempted to give quantitative structure to spatial experience and perception. Coining these 'location-specific patterns of visibility' or visibility polygons as isovists, **Figure 3.1**, Benedikt defined environmental perception as specific to the path along which an individual observes information about the surrounding environment, measured from points along the given path. He argued, 'an observer's perception is thus circumscribed, if not determined by the environment-as presented at the point of observation' (1979).

Because points along the path are contiguous (insofar as the individual is experientially concerned), the surrounding points may be described as an

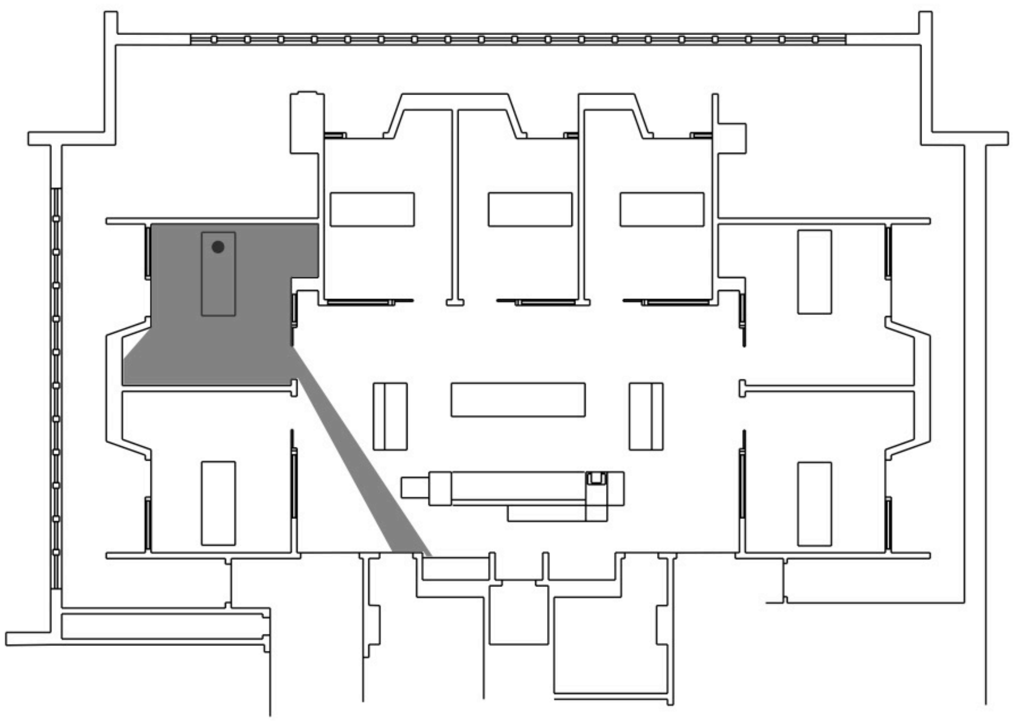


Figure 3.1 Isovist polygon as described by Benedict (1979), from Room C7, Unit C, Emory University Hospital. The isovist is generated from a single vantage point (shown as the HOB), and in this case, rotates around the point 360°. All shaded areas are visible to the vantage point; the vantage point is visible to all shaded areas.

informational field. Stated quantitatively, the area (and perimeter) visible around a vantage point constitutes a closed polygon (in interior settings), (Turner et al., 2001). Moving through space, the interplay between shifting isovists (or visibility polygons) completes an experiential description and provides information.

3.3.2 The Isovist as a Reciprocal Information Field

Although conceived from the observer's or vantage point perspective, the isovist also reveals information <u>about the vantage point (or 'x')</u> if examined from points in the informational field; the isovist provides reciprocal information. Benedikt (1979) affirms the notion of isovist reciprocity, suggesting that the size and shape of an isovist approximates the amount of information available to and about the individual at 'x'. A narrow, short isovist could yield very little information, while a long, wide isovist could reveal significantly more. The reciprocal nature of isovists allows a change of perspective: instead of being concerned with the view from 'x', the focus is on all points within the polygon from which visual connection can be maintained with 'x'. We acknowledge that the view from 'x' reflects the patient's ability to view clinical staff, surely providing a sense of comfort and contributing to a sense of personal safety.

This is intuitive – if the patient ('x') can see the nurse from the head of the bed, the nurse also has the potential to see the patient. That the nurse is facing the patient is not guaranteed, as the nurse could have his back turned and still be visible to the patient. There still exists, however, the potential, as opposed to a complete inability to visualize the patient if not within that isovist.

3.3.3 Isovist Set Choice

As a spatial, 'experience in space' measure, we must select a set of isovist-generating points within a setting (creating an isovist set) to fully describe the environment. How then, to choose? It is logical to select a set of vantage points that most closely describe the spatial system - termed 'a sufficient set' by Turner and colleagues (2001). This most economical set ignores route preference because of a desired vista (view) or shortest destination path, and yet is less biased, e.g. the personal nature of vista preference. In this way, however, the sufficient set may describe the spatial setting completely but sacrifice social meaning; we lose the 'desired experience in space' if a designated vantage point remains uninhabited, however economical. Even if we agree that a sufficient set appears necessary for a generic description of environments, it is found wanting in institutional settings precisely for this reason. The entire spatial system does not reflect the desired experience – only particular areas do so. We propose that the sufficient set is determined by the socio-spatial system.

In particular, two primary organizational considerations drive the desired experience in space for hospital settings: patient surveillance and organizational awareness (Dresser, 2012; Kelly & Vincent, 2011). The intensive care unit environment is most peculiar in that the nature of patient surveillance clearly defines without question, the patient as 'isovist-generating point', made easier because ICU patients tend to remain stationary. The patient-generated informational field constitutes a closed polygon; clinicians are the occupants. Clinicians are not afforded organizational awareness from the isovist (they are guaranteed awareness of the patient in question). As the other half of the desired experience in space, organizational awareness is derived from the meaning or value of those points in the information field. We propose that points within the patient-generated polygon provide differential visual access. Referring once again to **Figure 3.1,** consider the difference between locations in the polygon that is in the middle of the nurse station versus a location in the top right-hand corner of Room C7. Both locations have visibility to the patient, but differential visual access to the rest of the unit. We look to visibility graph analysis, namely connectivity, to assign informational field point value.

3.3.4 Local and Global Spatial Measures

In "The Social Logic of Space", Hillier and Hanson (1984) define *space syntax* as the study of the actual and social organization of inhabited spaces as configurations, e.g. rooms and hallways that are connected and patterned into meaningful relationships. Stated more simply, space syntax is a theory of architectural layout, which is the arrangement and connection between spaces in the built environment, and which provides opportunities for movement and interaction, namely access (control) and exposure (privacy). Similar to the isovist discussion, layout affords visual information exchange during movement. These arrangements and connections (layout) also display social differentiation and support social organization; that is, spaces reflect their inhabiting society.

For example, upon attempting to enter a patient care unit, we might first encounter a staffed desk, which serves as a boundary to the patients and staff, both controlling movement into the unit and supporting the privacy of those in the unit. The arrangement and organization of space affects movement and interaction probabilistically above and beyond cultural and organizational norms - the relationship is dynamic (Bafna, 2003). That we might further explain probabilistically influenced movement and interaction, we must first discuss the method and metrics by which this determination is possible.

Each space as 'an arranged connection' on a floor plan is assigned a numerical value on the basis of its relationship or connection, to the other spaces. A space could be an entire room or hallway on a floor plan, termed a 'convex space'[3]; crossing from one convex space to another constitutes a boundary crossing, which forms the basis of spatial analysis.   A geometrically smaller (and less arbitrary) unit of analysis is the square tile centroid (Haq & Luo, 2012). Arranged as a continuous square set over a floor plan (tessellation), and broken only by walls, (the size of the tile depends upon the granularity required), the interrelationship of the tiles is analyzed in the same way as if a convex space. Crossing from one tile centroid to another, much as on a chessboard, constitutes a 'boundary crossing' and can be quantified.

Connectivity, considered a 'local measure', calculates the number of tiles (centroid) directly connected to the tile (centroid) in question, 'x', (via an imaginary straight line) without a change in direction. A higher connectivity

[3] Rooms/hallways are geometrically described by the fattest, for lack of a better term, convex polygon that can be drawn within the boundaries of a room, termed a convex space. There is visual reciprocity from all points within the convex space. An L-shaped room, for example, will require 2 convex polygons to cover all boundaries. Boundaries occur at the interface between convex spaces.

value tile has more directly connected tiles; the converse is also true. Possible connections via a change in direction (not a straight line) are not included in the connectivity score. *Integration*, a measure of how many changes in direction, on average, the tile in question, 'x', is from *all other tiles (centroid)* is considered a 'global measure', reflecting an entire system. Mathematically expressed as an inverse ratio, the higher the integration value of 'x' (the tile in question), the more tiles 'x' is connected to, via a straight line, without changing direction. All tiles directly connected to 'x' are termed to be a 'step depth of 1', without regard to distance (although a distance limit is possible). One turn beyond direct connection is termed a 'step depth of 2', and so on.

Spatial analysis (connectivity, integration, and a host of other measures), is most often calculated with software – UCL Depthmap (Turner, 1998). In addition to providing a numerical value for each tile (centroid) by variable in a spreadsheet format, Depthmap translates the numerical variables and values into a color spectrum of tiles on the floor plan for visualization, displaying the pattern of connectivity, for example, **Figure 3.2.** Analyses can be run as if the tiles are parallel to the floor at knee level, termed an accessibility analysis, or at standing/seated eye level, termed a visibility analysis. An accessibility analysis is typically conducted for questions related to pedestrian movement on city streets, for example. An accessibility analysis would artificially limit our understanding of information exchange; I may not be able to walk through the nurse station desk, but can see those beyond. Note that in a visibility analysis, see-through glazing is not considered a barrier, where as it would be considered a physical barrier in an accessibility analysis.

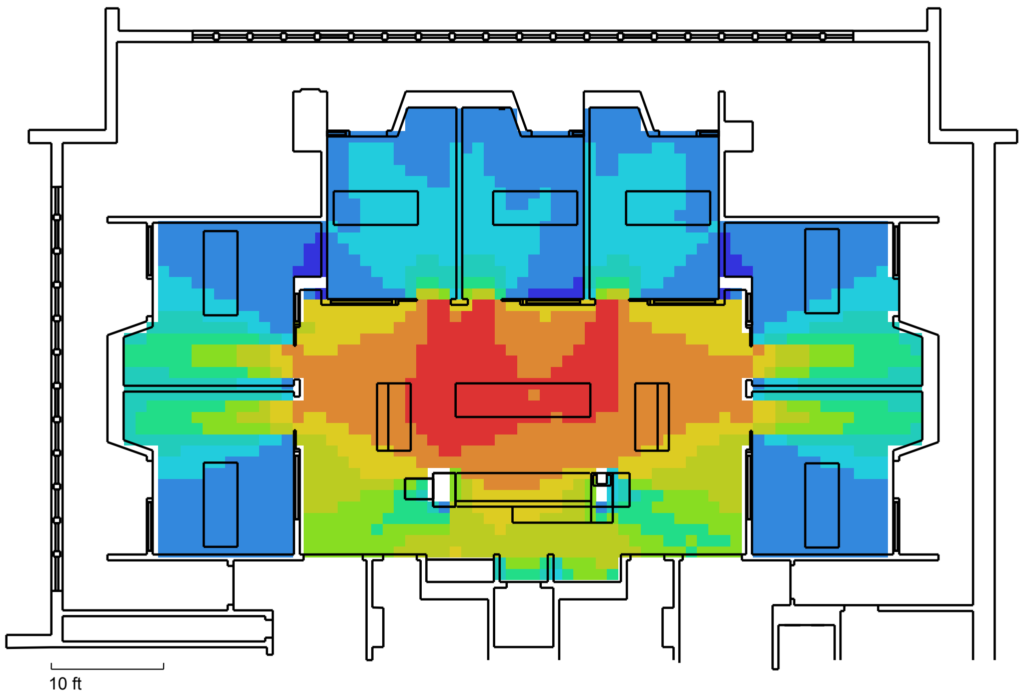


Figure 3.2 Connectivity graph example, ICU C. Visibility analysis ('tessellation' occurs at standing eye-level), revealing the tile centroids with the most direct connections in red (central nurse station), and the tile centroids with the least direct connections in blue.

3.4 Relating Spatial Measures and Behavior

3.4.1 Foundations

Much of the initial work exploring how and why individuals move through space began in exhibition settings, but has theoretical application to the inpatient setting. Choi (1999), for example, sought to increase the understanding of the relationship between layout, visitor movement, and 'a field of reciprocal social visibility'. Through behavior mapping, tracking, and syntactic analysis across 8 museums, Choi (Choi, 1999) found that highly integrated spaces did not have more people in them; highly integrated spaces provided views of more people. Peponis and colleagues (2004) reported that during museum exploration, visitors were measurably more aware of freestanding exhibits that had higher visual connectivity scores and lower mean depth (more integrated). Interestingly, active engagement with an exhibit was associated with being able to view another exhibit concurrently, a finding that extends to surveillance behavior and collaboration. Similar to visitors engaging in museum exploration, clinicians engage in patient surveillance and co-worker awareness; the parallel argument being that nurses may be more aware of colleagues in areas with higher visual connectivity. The concurrent visibility described by Peponis and colleagues is a theoretical basis for isovist connectivity, whereby a nurse seeks to both supervise her patients and remain connected to the rest of the unit.

There is precedence for merging isovist and visibility graph theory. Peatross (2001) investigated the balance between environmental control and freedom of movement in mid-range restrictive institutional environments: 3 Alzheimer's long-term care units and 3 juvenile detention centers. The author theorized that spatial control was determined by which group – staff or residents – had visual overview of potentially occupied space. Peatross measured the field of awareness with a new density measure, the 'animated isovist', calculated as the occupancy ratio by social role and activity (moving or sitting), of individuals located within the largest polygon possible within a space.

Most interestingly, weighed densities (density weighted by number of people available to populate a space) were significantly correlated with integration. Peatross concluded that even in restrictive settings, people move where they can see and be seen, above and beyond where they are supposed to be located in space. Nurses are also subject to tacit and overt restriction of movement, required to 'be by the bedside', and to let a colleague know when they are 'going off the unit'. Like the residents and staff in Peatross' study, nurses may choose to locate themselves where they can see and be seen by others above and beyond their required location. Furthermore, the configurational characteristics of a patient care unit may influence where a nurse lingers and what path she takes.

3.4.2 Isovist Connectivity Theory and History

In 2007, researchers at Georgia Institute of Technology conducted an unpublished pilot study in a neurosciences ICU (NSICU) at Emory University Hospital with the intent of generating hypotheses about the distribution patterns of staff members in space, according to generic visibility graph measures. The researchers found no particular pattern of spatial occupation, other than expected at high integration points, at nurse stations, and in rooms. Two methodological directions emerged from this pilot work: targeted visibility (Lu, Peponis, & Zimring, 2009), and isovist connectivity.

Lu, Peponis, and Zimring (2009) presented a paper at the 2009 Space Syntax Symposium hypothesizing that clinicians are interested in a specific target, namely the patient head of bed (HOB) during movement through space - a metric titled 'targeted visibility (TVi)'. Lu and colleagues (2009) compared the density of clinicians (n=946) by role and interaction status against TVi and generic visibility (e.g. connectivity and integration). A person was defined as interacting if in active conversation with another person, i.e. listening or speaking. No inter-observer agreement was measured. For the NSICU **(Figure 3.3)**, the TVi values ranged from 0-9, according to the maximal and minimal number of heads of beds it was possible to view at one time. The range of connectivity scores (85-4555), were artificially divided into 10 equal level intervals, to allow comparison against the 10 TVi levels.

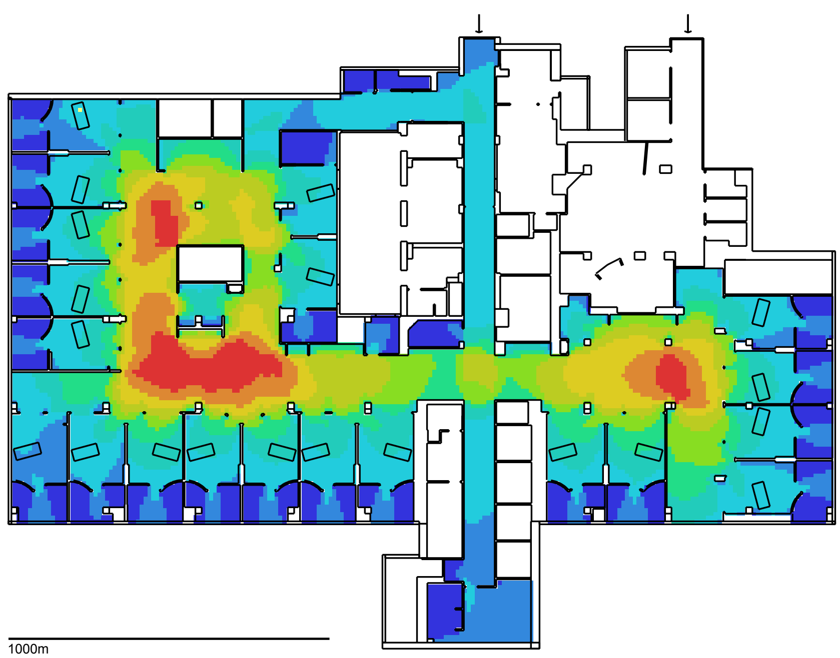


Figure 3.3. Visual Connectivity graph, NSICU, Emory University Hospital.

Physician density did not correlate with TVi, whether interacting or not, suggesting no particular preference for HOB visibility. The density of both interacting (n=133) and non-interacting physicians (n=187), however, was correspondingly related to the rank of the connectivity score, (r=0.811, p=0.004 and r= 0.747, p=0.013 respectively). These density patterns suggested that whether interacting or not, physicians appeared to prefer locations with higher connectivity scores (higher general awareness potential, rather than targeted to patients). It was unsurprising that physician density was distributed by generic connectivity, appropriate to a broader supervisory and care role and giving them the best possible purview of the entire unit. However, we cannot know the potential effect of resident physicians (who may be responsible for a smaller patient subset) nor of consulting physicians (who may see one patient). These physician types may exhibit the behavior patterns of the nurses, discussed below.

Density for interacting nurses (47%) was significantly correlated with TVi (r=0.894, p<0.001) and with higher connectivity scores (n=333) (r=0.817, p=0.004), suggesting a preference to survey more patients and have general awareness while interacting. Nurses may also have been interacting with physicians when in areas with higher connectivity, rather than having nurse-nurse interactions, for example, in higher connectivity areas. However, non-interacting nurses (53%) did not exhibit higher density patterns in areas with higher TVi (r= 0.566, p=0.088) nor in areas with higher connectivity (r=0.359, p=0.309), suggesting a more even distribution of non-interacting nurses across all spaces in the unit.

Apart from documenting the presence of people, this study suggested potential architectural and patient safety implications. Patients near higher connectivity score areas may benefit from greater physician presence. Conversely, patients near lower connectivity score areas may suffer when nurses move to higher connected areas (whether drawn to physician interaction opportunities or location of support areas – medications, supplies, etc.). Interaction aside, however, both generic measures (connectivity) and targeted measures (TVi) were unrelated to non-interacting nurses, which in this study, was half the sample population.

3.5 Combining the Isovist and Connectivity

The relationship – or lack thereof – between staff member distribution patterns in space and spatial measures in the 2007 pilot study was surprising. The Lu et al. (2009) study was unable to account for the movement of non-interacting nurses. In other settings (e.g. museums), spatial metrics reflected purview and movement, but there was no dual requirement of particular areas of foci and awareness. In response, we (M.O. and S.B.) conceptualized the measurement of these dual affordances in *isovist connectivity*. Since published works illustrate the need for further metric refinement; the primary methodological assumption has been clinician positioning at team stations, even given the plethora of research documenting nurse walking times. We propose spatial metrics that consider additional occupied areas, e.g. corridors.

3.5.1 Definition of Isovist Connectivity

Isovist connectivity (IC) is defined for a single vantage point. Notionally, the isovist connectivity of a point is the average area of the isovists of all points in the isovist of the point. Isovist connectivity is easier to compute with the way isovist of a point is implemented in Depthmap—that is, as a set of points directly visible from the reference point. This means that, effectively, the isovist connectivity of a point is the average connectivity of all the points in the isovist of the point. The isovist connectivity of a polygonal region can be simply computed by averaging the isovist connectivity of all individual vantage points included within the polygon, **Figure 3.4**.

3.5.2 Calculating Isovist Connectivity

There are likely several ways to derive what is essentially 'the isovist of every tile in the isovist', however we chose to do so using step depth. *A step depth*[4] of 1 approximates the isovist, by 'revealing' all the tiles that have a direct connection, or mutual visibility, to the vantage point(s). In UCL Depthmap, this calculation is possible by utilizing the *step depth* analysis. It is possible to select, for example, the 16 tiles or 4 square feet that make up the head of the patient bed, and search for all mutually visible tiles, **Figure 3.5.**

Isovist connectivity calculation steps are as follows: (1) run a visibility graph analysis for the floor plan; (2) run a step depth analysis for each tile or tiles of interest (saved as individual analyses); (3) use the resulting spreadsheet to filter for those tiles with a step depth of 0 (the selected tiles) and 1 (directly connected tiles) by individual analysis; and (4) calculate the arithmetic mean of

[4] Step Depth is not to be confused with the notion that the next tile is literally 'one step away'. Step Depth of 1, for example, connotes mutual visibility between the two points in question.

the generated set of connectivity values[5], (unique to originating tiles). The result is an isovist connectivity score for each set of originating tiles, **Table 3.1.**

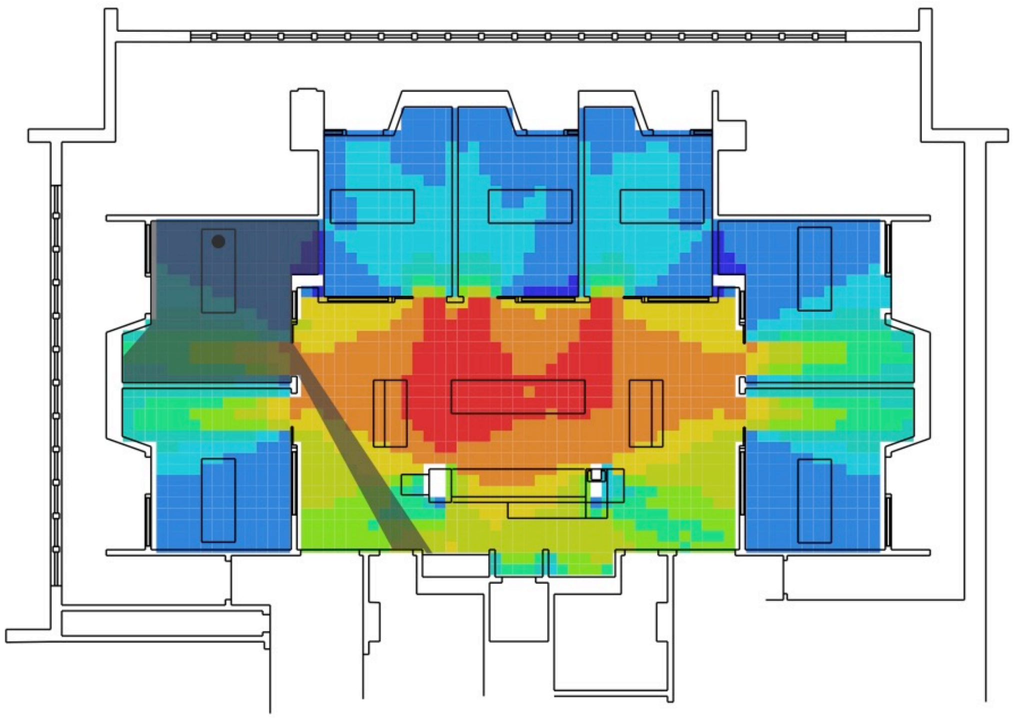


Figure 3.4. Isovist connectivity can be conceptualized as calculating the average connectivity of the isovist. Shown here, the isovist polygon for Room C7 is layered over the connectivity graph. The connectivity values of the tile centroids that make up the area of the isovist polygon are the tile centroids of interest.

[5] Each tile also has other values – integration, etc.

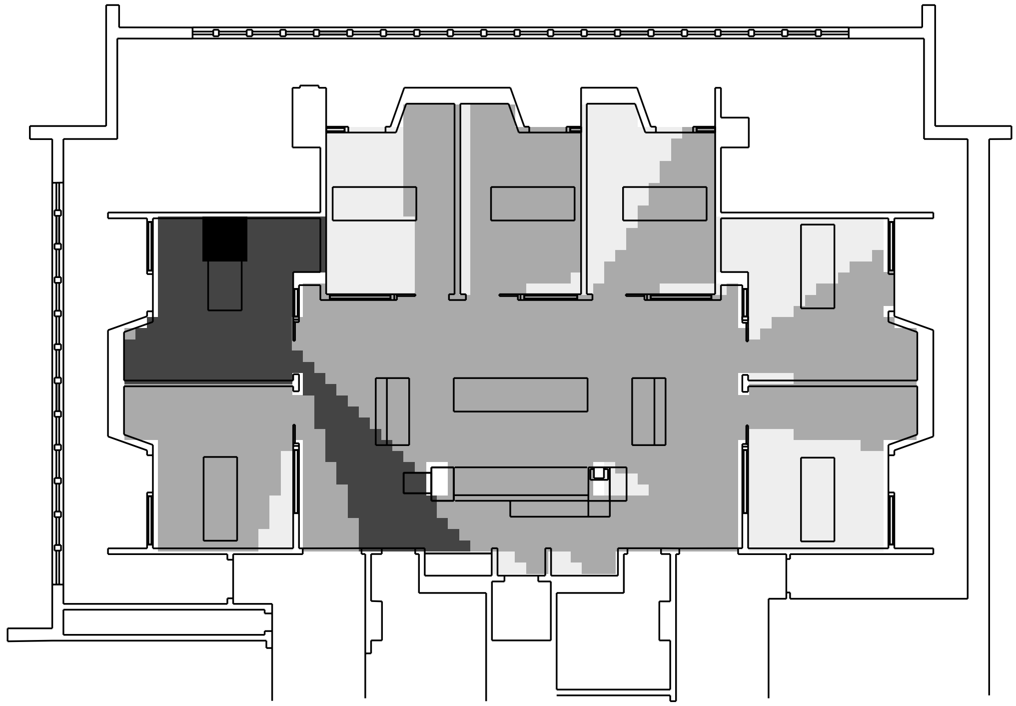


Figure 3.5. Step depth (SD) Graph, Room C7. 'Dark Gray' tile centroids (SD = 1) are mutually visible to the set of selected tile centroids, in this case, the head of bed (SD=0); 'Medium Gray' tile centroids (SD = 2) are 1 turn away from mutual visibility; 'Light Gray'' tile centroids (SD = 3) are 2 turns away from mutual visibility.

Table 3.1. Depthmap Table sample for Room C7, generated from the head of the bed (HOB). XY coordinates map to specific tiles. Filtered for tiles with a SD = 1. The average of the corresponding connectivity values (with a SD of 1) results in the isovist connectivity value.

X	Y	C7 HOB SD	Connectivity
11	46	1	497
11	47	1	548
11	48	1	608
.	.	.	.
n	n	1	n
			AVG = 1080.21

3.6 Isovist Connectivity – Meaning and Significance

Spatial variables predict locational preferences in a myriad of settings, and are clearly associated with movement and interaction. Healthcare environments are no different with one caveat: patient observation is a critical and essential job function. We seek to capture this complex visual condition with isovist connectivity, as an environment that affords both patient observation and visual access may impact patient safety. Isovist connectivity of a region, such as square marking the head of a patient bed, therefore, provides a measure of the quality of visual access to the entire layout available to anyone who is at the same time keeping the head of the bed in surveillance. Higher isovist connectivity values associated with a region should allow a person to visually survey larger areas of the nursing floor while monitoring a patient, and allow him or her better organizational awareness. In theory, therefore, higher isovist connectivity of a region should correspond with better patient outcomes.

The first step was to develop rigorous spatial metrics; the next is relating meaning. In Chapter 4, we will demonstrate a significant and direct relationship between isovist connectivity and ICU survival. It is likely that the mechanism of patient survival as predicted by isovist connectivity, is the presence of people. Layouts that provide for patient observation and visual access (as measured by highly connected isovist polygons) may experience higher clinician density thereby conferring decreased risk. It is beyond the scope of this paper to fully explore the relationship between isovist connectivity and the density of people, but we acknowledge that necessity as a next step.

CHAPTER 4

VISIBILITY + ICU MORTALITY

4.1 Abstract

Objective: Limited evidence suggests that intensive care unit (ICU) survival is associated with visibility, particularly for patients with severe critical illness. The potential patient and organizational implications are significant, but must be validated in other settings and populations. The purpose of this study is to validate the relationship between visibility and ICU mortality.

Design: Retrospective cohort study.

Setting: 3 medical ICUs (MICUs) and 1 medical-surgical ICU (MSICU) across 2 hospitals within the same tertiary academic medical center.

Patients: All patients admitted to 4 ICUs between September 2011 and June 2014 with a sepsis discharge diagnosis, DRG 870-2.

Interventions: None.

Measurements and Main Results: A total of 1,385 patients were eligible for inclusion. We conducted a spatial morphology analysis of the architectural floor plans and physical characteristics for each ICU, generating an isovist connectivity (IC) score. ICU mortality was then compared by patient assignment to a low (n=877), medium (n=311), or high (n=197) IC score room across all ICUs. Unadjusted mortality for low, medium, and high visibility rooms were15.7%, 13.8%, and 10.2%, respectively. After adjusting for patient characteristics, patients exposed to a high IC score room experienced at 42% lower odds of death compared to patients exposed to a low IC score room, p= 0.048, CI 95%; the

medium IC score rooms trended similarly, although conferred no statistically significant effect, as measured by isovist connectivity.

Conclusion: Consistent with previous studies, poorly visible and less connected rooms are independently associated with higher ICU patient mortality. Furthermore, the highly visible and connected rooms were not distinct from those less so – all rooms met current SCCM ICU design guidelines for patient visibility - suggesting the need for robust spatial analysis to determine level of visibility afforded to each room.

4.2 Introduction

4.2.1 Background

Emerging evidence shows that the spatial layout of intensive care units can be a risk factor for patients, over and above any patient characteristics. A recent study of a medical intensive care unit (MICU) at Columbia University Medical Center found that field of view (defined as the maximum viewing angle from the patient head to the rest of the unit) predicted 33.5% of the variance in ICU mortality for very ill patients (APACHE II scores >30), after controlling for patient characteristics (66.7% mortality rate for low visibility rooms vs. 46.7% mortality rates for high visibility rooms) (Lu et al., 2014). Further work is necessary, however, to evaluate the robustness of this relationship in different populations and with refined visibility metrics. This study will compare a novel visibility measure with mortality rates in sepsis patients.

The rationale for selecting sepsis, DRG 870-872, has several origins. First, accepted acuity scales exist for patient differentiation; this study will use the Sequential Organ Failure Assessment (SOFA) score[6] and the Charlson Comorbidity Index (CCI). Second, the burdens associated with sepsis are enormous: treatment in the US ran at an estimated $20 billion (5.2% of total US hospital costs) in 2011 (Torio & Andrews, 2013) and patients with sepsis had an average length of stay 75% greater than those without the diagnosis of sepsis (M. J. Hall, Williams, DeFrances, & Golosinskiy, 2011).

Despite the resources required to treat sepsis, sepsis is a leading cause of death and those who survive have an increased likelihood of long-term negative sequelae (Hall, et al., 2011). Because the burden associated with sepsis is so high, numerous clinician researchers and programs are devoted to developing bundles (*Severe Sepsis Bundles*, 2013), checklists/guidelines (Dellinger et al., 2013), cultural interventions, and most recently, revised sepsis definitions (M. Singer et al., 2016) to streamline, standardize, and improve care. Most solutions, however, ignore the 'built environment' component within the structure-process-outcomes framework (Donabedian, 1978), **Figure 4.1**; the physical environment is either unnoticed or viewed as a static variable.

Collaborative studies, however, from human factors, systems engineering, and architectural fields identify the physical environment as impeding clinician work, e.g. "Patient's rooms not close to each other", (Gurses & Carayon, 2007; 2009)

[6] The definitions, criteria, and administrative coding for sepsis in this study are based upon the 2001 recommendations (Levy et al., 2003).

and "Layout not conducive to patient care", (Tucker, Singer, Hayes, & Falwell, 2008). Moreover, layout (the organization of rooms and connecting spaces) was implicated in impeding time to being seen (K. Hall et al., 2008), impacting the length of time and frequency with which a nurse enters a patient room (Hendrich et al., 2009; Lu, 2010), influencing patient observation (Hendrich et al., 2004; Hurst, 2008), and staff communication (Gurses & Carayon, 2007; Rashid, 2009). This cumulative body of work suggests that the physical environment influences the process of care, and an enhanced understanding of this relationship can have important implications both for existing ICUs and the design of future ICUs to mitigate visibility problems. Our model is grounded in Donabedian's work, whereby concurrent visibility (structure) and patient surveillance and organizational awareness (process) affect ICU mortality (outcome).

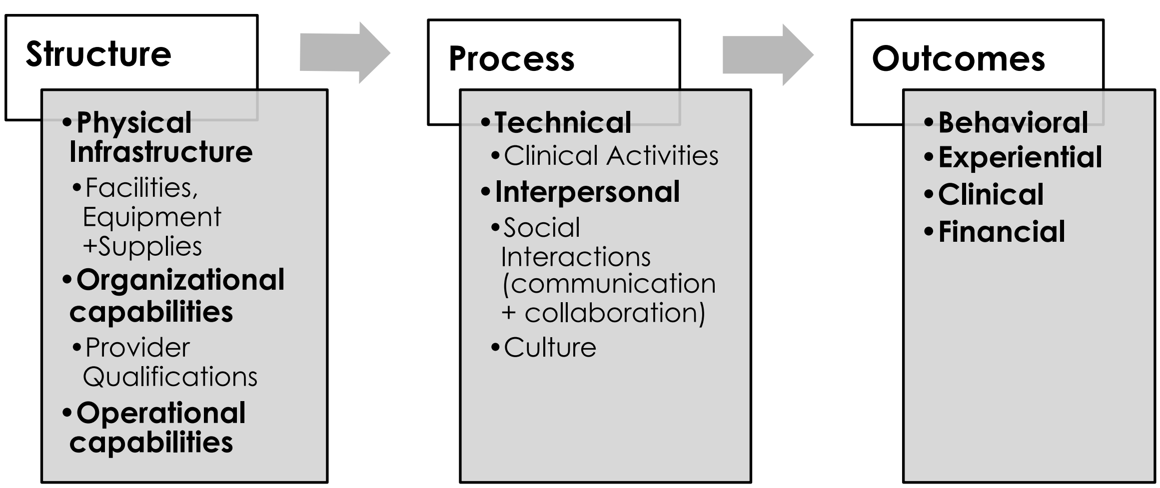


Figure 4.1. Structure-Process-Outcomes Model (Donabedian, 1978)

4.2.2 Spatial Variable Development

We constructed a predictor variable based upon concurrent patient and co-worker visibility, namely isovist connectivity. Isovist connectivity (IC) reflects the conceptual merging of two well-established, empirically derived architectural constructs: the isovist and connectivity.

An isovist is the area visible around a point or target (in this case, the patient head of bed), which constitutes a closed polygon (Benedikt, 1979; Turner et al., 2001), **Figure 4.2.** The isovist is a visual, reciprocal information field; all points within the polygon can see the target and vice versa. The isovist reveals, therefore, all spaces where a clinician may locate and maintain direct visualization of the patient.

Like the isovist, connectivity reveals direct, visual connections from a given point in space, and is not limited by distance (although a distance limit can be used if so desired), **Figure 4.3.** Instead of generating a polygon, however, a connectivity analysis produces a 'score', a literal number of points or tile centroids. The higher the connectivity value of a point, (shown as a tile in the visual representation) the higher the number of points connected to the point in question. Across an array of built environment settings, e.g. museums, offices, and other institutional environments, connectivity (and other spatial metrics) is associated with visual awareness, the presence of people, and movement (Peatross, 2001; Peponis et al., 2004).

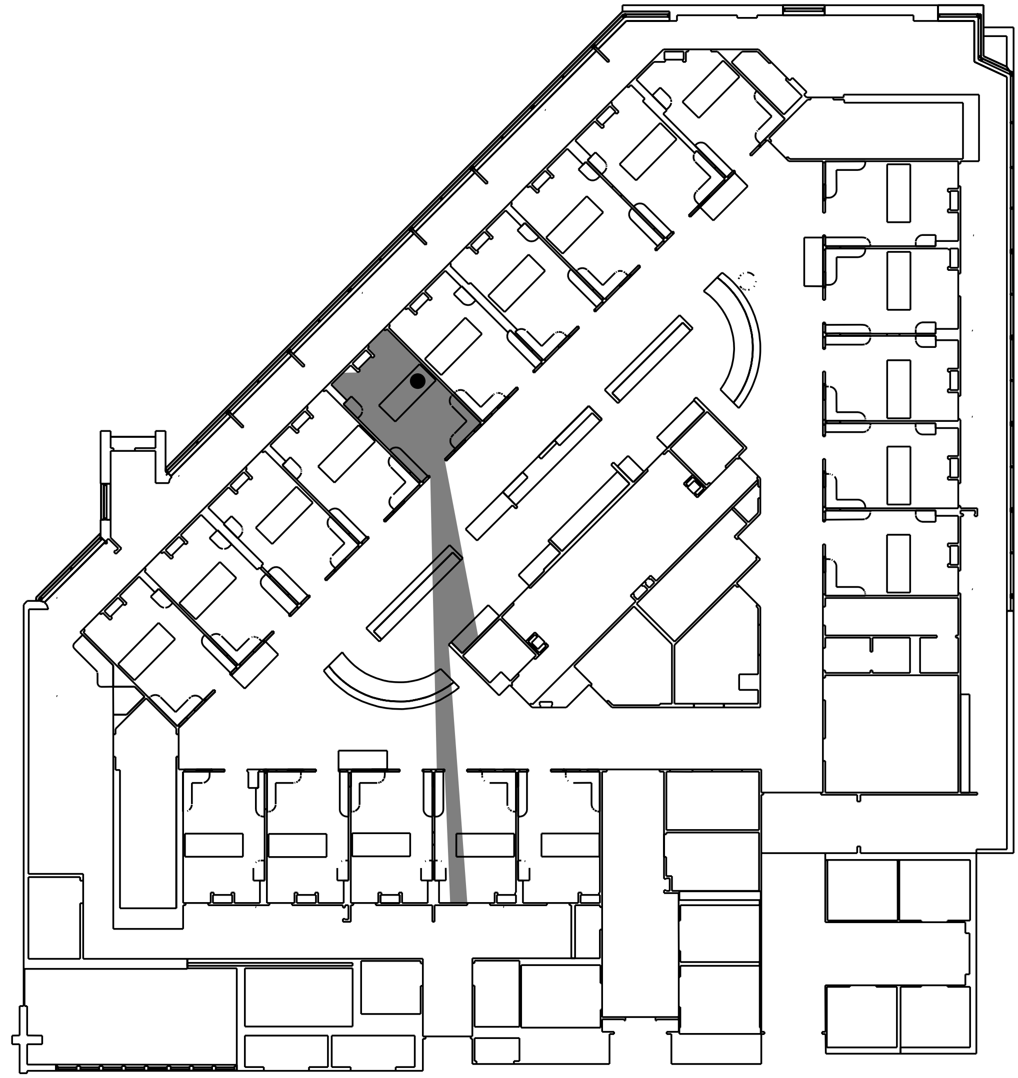


Figure 4.2 Example of an isovist polygon from Room A11, ICU A. The isovist is generated from a single target (shown as the HOB), and in this case, rotates around the point 360°. All shaded areas are visible to the target; the target is visible to all shaded areas.

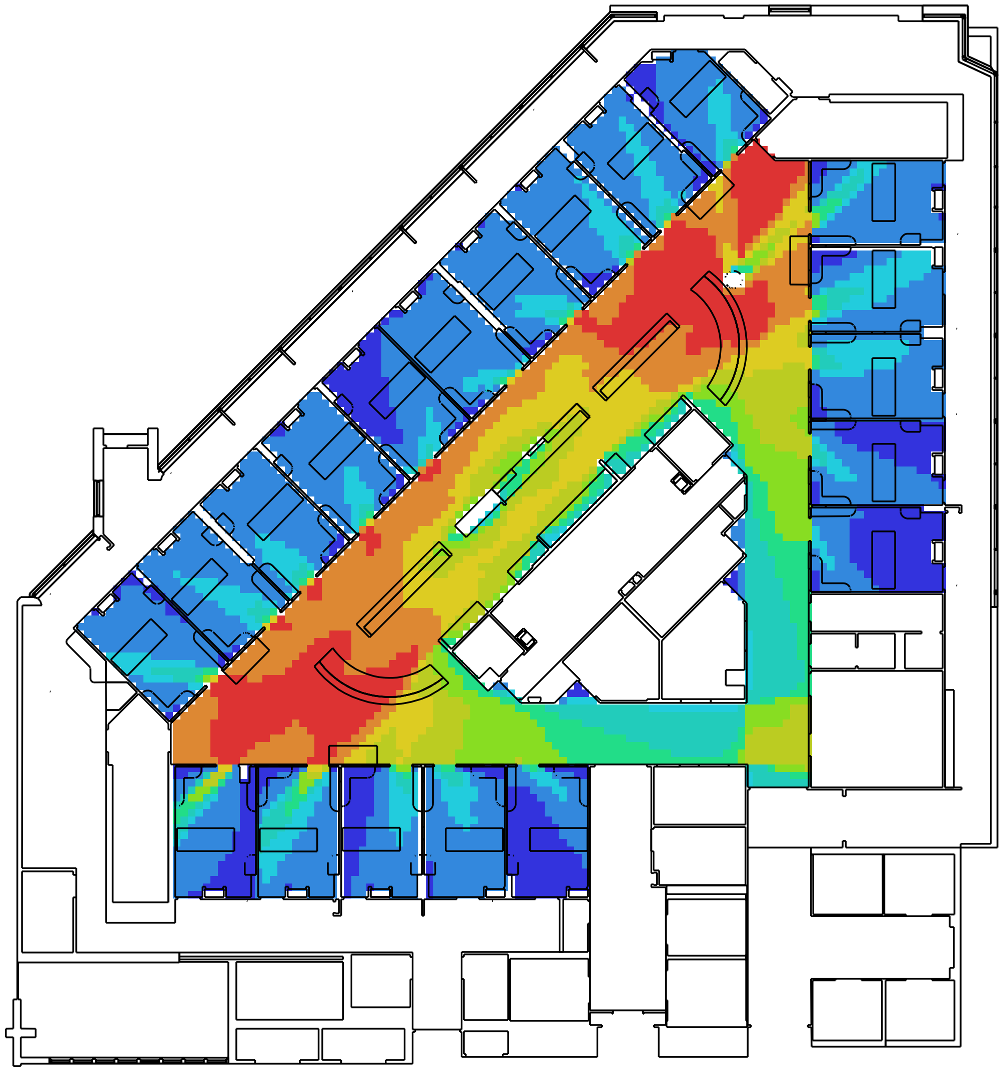


Figure 4.3 Example of a Connectivity graph, ICU A. Visibility analysis ('tessellation' occurs at standing eye-level), revealing the tile centroids with the most direct connections in red, and the tile centroids with the least direct connections in blue.

We view the isovist and connectivity as insufficient in isolation, however, to capture the work of clinical care. The size of the isovist of a point (or the connectivity of a point), while showing all reciprocally visible spaces, does not capture some key attributes of the isovist, which are critical to clinical activities. Among other spatial qualities, one such attribute is the area of layout visible from the different points within the isovist, which contribute to visual access and patterns of local movement. Isovist connectivity is designed to capture this attribute.

4.3 Methods

4.3.1 Study Design and Population

We conducted a retrospective single-center cohort study of all adults with a sepsis discharge diagnosis using administrative coding (i.e. DRG 870-2) who were admitted to four Emory ICUs between September 1, 2011 and June 30, 2014. We excluded those with intra-unit bed transfers or ICU readmissions from the analysis. Architectural floor plan verification and analysis occurred prospectively.

4.3.2 Setting

Emory Healthcare, Atlanta, GA, is an academic tertiary referral center with 4 hospitals, 12 ICUs, and 173 critical care beds, with over 10,000 admissions annually. We selected 4 ICUs for inclusion across 2 of the 4 hospital campuses that varied in architectural configuration: Emory University Hospital (ICU A, B, and C) and Emory University Hospital Midtown (ICU D). All 4 ICUs share similar standardized care protocols. Emory University Hospital achieved Magnet designation in early 2014.

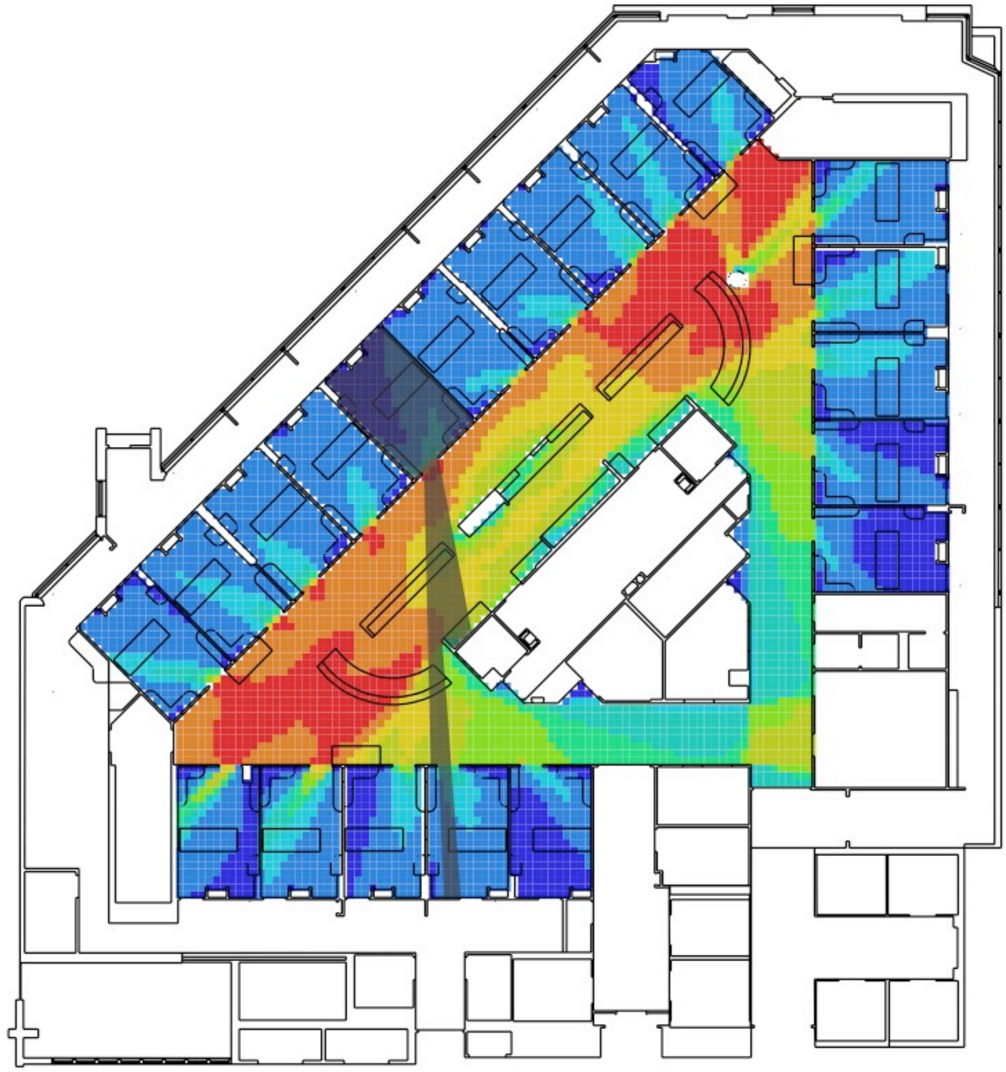


Figure 4.4 Isovist Connectivity can be conceptualized as calculating the average connectivity of the isovist. Shown here, the isovist polygon for Room A11 is layered over the connectivity graph. The connectivity values of the tile centroids that make up the area of the isovist polygon are the tile centroids of interest.

4.3.2.1 ICU A, Emory University Hospital

ICU A is a 20-bed medical-surgical ICU, with an average daily census of 17.2 (2.1 SD) and 1380 encounters in FY2015. Medical staffing consists of a board-certified critical care attending physician 7 days a week with 3-8 resident physicians and 2 fellows at all times from the following programs: pulmonary/critical care, surgical critical care, anesthesiology/critical care, and neurocritical care. Advance practice providers (APPs, i.e. nurse practitioners and physician assistants cover the unit 24 hours a day, 7 days a week (1-2 per 12-hour shift). Daily rounds take place 3 times day / 7 days a week. ICU A is semi-closed; admissions occur 24 h per day from the emergency department, general wards, and from outside hospitals. The charge nurse assigns patient rooms according to bed availability unless as required for respiratory isolation.

Nurse-to-patient ratios are 1:2 on both 12-hour shifts, 7 days a week, but may decrease to 1:1 upon higher patient acuity. Nurses use a ‘buddy system’ for coverage for break (15 min) and lunch (30 min) relief, resulting in a transient increase to 1:3 for 1.5-hours/per patient each day.

ICU A was constructed in 1987 with a triangular typology and is approximately 8830 ft^2, excluding family waiting (2688 ft^2), **Figure 4.5.** The 20 non-uniform patient rooms vary from 185-199 ft^2 of clear floor space. Room A15 is equipped for respiratory isolation. There are separate circulation cores for staff and families such that each patient room has double entrances and no direct view to the outside. The team station is centralized by design, however 4 distributed charting locations are present

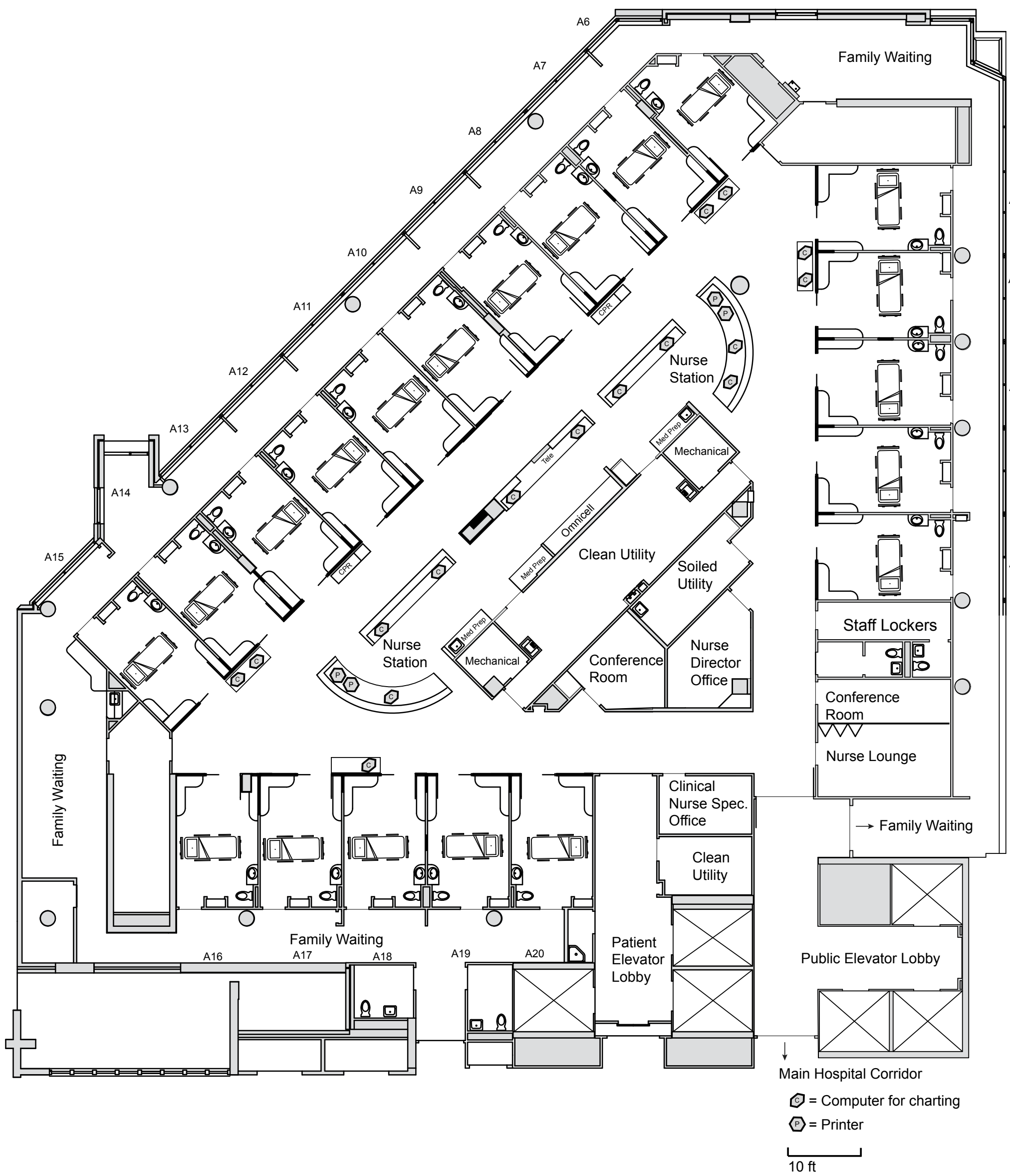


Figure 4.5 Unit A, Emory University Hospital. Note that the only visual opening shown to each patient room is the open door.

(2 per corner in 2 of 3 corners) and bedside charting is available in each patient room. Supplies and medications are centralized behind the team station. The glazing (windows) for each patient room to the staff core vary by patient room and with the exception of the doors (which are completely glazed), begin at 38" from the floor. Visual information displays (white boards, chart holders,

paper holders/displays) and supply holders (e.g. personal protective equipment, PPE) are affixed to numerous windows and glazed doors, for example, **Figure 4.6.**

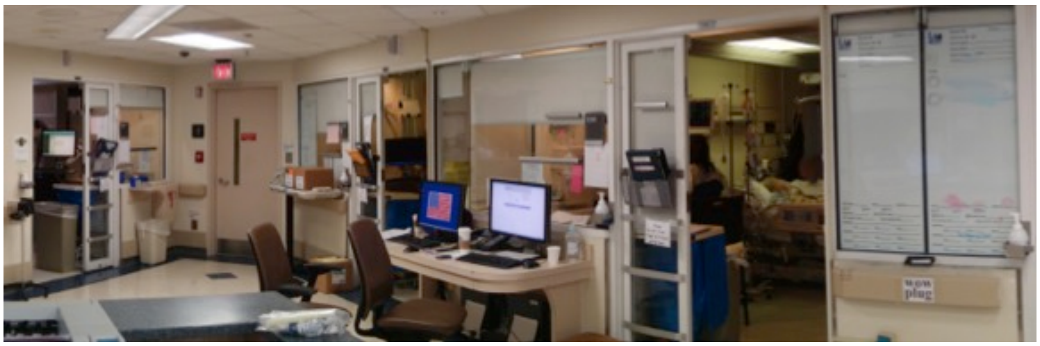


Figure 4.6. Corner view of Rooms A14-A16. Note opaque visual information displays affixed to glazing. Also note example of distributed charting station.

<u>ICUs B & C, Emory University Hospital</u>

ICUs B and C are 7-bed medical ICUs (total 14 beds), vertically stacked in the same wing and connected by a stairwell located just outside each unit's entrance. These units operate organizationally as a single MICU. Across this 14-bed ICU, the average daily census is 12.6 (1.3 SD); 1214 encounters in FY2015. Medical staffing consists of a board-certified critical care attending physician 7 days a week with 4-5 resident physicians and a pulmonary-critical care fellow. Advance practice providers (APPs, i.e. nurse practitioners and physician assistants cover the unit 24 hours a day, 7 days a week (1 per 12-hour shift). Daily rounds take place 2 times day / 7 days a week. ICUs B and C are closed; admissions occur 24 h per day from the emergency department, general wards, and from outside hospitals. The charge nurse assigns patient rooms according to bed availability, unless as required for respiratory isolation.

The nursing pool can be assigned to either floor. Nurse-to-patient ratios are 1:2 on both 12-hour shifts, 7 days a week, but may decrease to 1:1 upon higher patient acuity. The odd number of beds, (7/unit), ensure a single 1:1 assignment if fully staffed. Nurses use a 'buddy system' for coverage for 2 15-minute breaks and lunch (30 minutes) relief, resulting in a transient increase to 1:3 for 2 hours/per patient each day.

ICUs B and C were constructed in 1972 with a U-shaped typology (James &Tatton-Brown, 1986) and are each approximately 2973 ft^2, excluding family waiting (1296 ft^2), **Figures 4.7 and 4.8.** The 14 non-uniform patient rooms vary from 169-206 ft^2 of clear floor space. All rooms in ICU B are equipped for respiratory isolation. There are separate circulation cores for staff and families; each patient room has double entrances and no direct view to the outside. The team station is centralized by design and bedside charting is available in each patient room. Supplies and medications are centralized behind the team station. The glazing for each patient room to the staff core varies by room, and with the exception of the doors, which are wood inset with glazing and uniform across all rooms, begin at 38" from the floor. Visual information displays (white boards, chart holders, paper holders/displays) and supply holders (e.g. PPE) are affixed to numerous windows and glazed doors, for example, **Figure 4.9.**

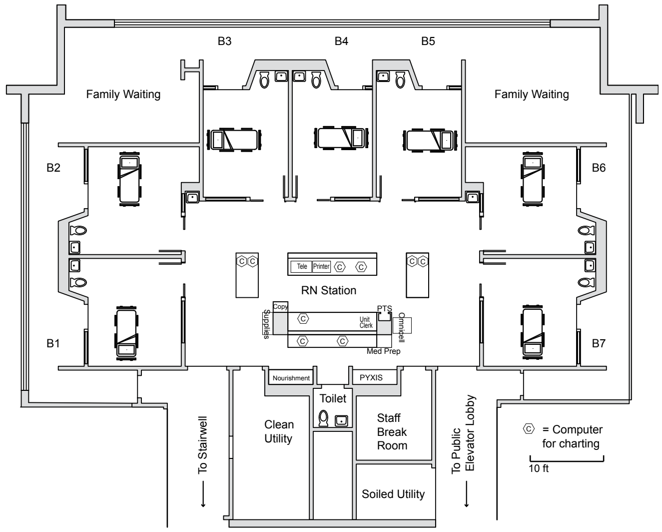


Figure 4.7. Unit B, Emory University Hospital. Note that the only visual opening shown to each patient room is the open door.

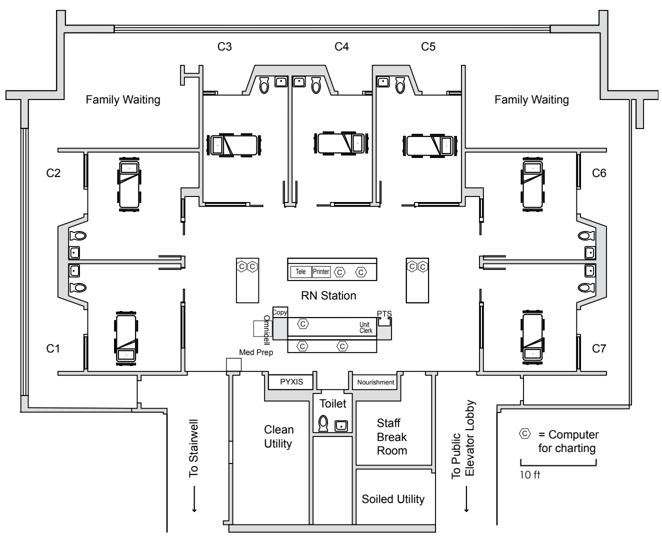


Figure 4.8. Unit C, Emory University Hospital. Note that the only visual opening shown to each patient room is the open door.

Figure 4.9. Room B17. Note 'drawn' visual information displays and PPE affixed to the door.

ICU D, Emory Midtown Hospital

ICU D is a 20-bed medical ICU, with an average daily census of 16.4 (2.5 SD) and 1444 encounters in FY2015. Medical staffing consists of a board-certified critical care attending physician 7 days a week with 3-5 resident physicians and a pulmonary-critical care fellow. Advance practice providers (APPs, i.e. nurse practitioners and physician assistants) cover the unit 24 hours a day, 7 days a week (2 from 0700-1900; 1 from 1900-0700). Daily rounds take place 3 times day / 7 days a week. ICU D is closed; admissions occur 24 h per day from the emergency department, general wards, and from outside hospitals.

Nurse-to-patient ratios are 1:2 on both 12-hour shifts, 7 days a week, but may decrease to 1:1 upon higher patient acuity. Nurses use a 'buddy system' for coverage for 1 15-minute break and lunch (30 min) relief, resulting in a transient increase to 1:3 for 1.5-hours/per patient each day.

ICU D was constructed in 2009 with a mixed typology – double corridor and U-shaped (James &Tatton-Brown, 1986), **Figure 4.10**. The double corridor section is approximately 3969 ft^2 with 8 uniform patient rooms (220 ft^2 of clear floor space). The U-shaped section is approximately 4134 ft^2. The 12 non-uniform patient rooms vary from 160-172 ft^2 of clear floor space; the corner rooms are at 223 ft^2 clear. Rooms D9 and D20 are equipped for respiratory isolation.

Staff and families share a single circulation corridor with single patient room entrances and a direct view to the outside. The team station is centralized by design and bedside charting is available in each patient room. Supplies and medications are duplicated and centralized in the double corridor and U-shaped sections and distributed outside each patient room.

The glazing for each patient room to the staff core varies by room and is essentially by means of a glazed door. The double corridor section (Rooms D1-D8) has a small window for each room that is typically obstructed by curtains and information displays. The U-shaped section does not have additional windows, with the exception of Rooms D9 and D20, both of which have permanently frosted (opaque) windows. Visual information displays (paper holders/displays) are affixed to numerous windows and glazed doors, **Figures 4.11 and 4.12.**

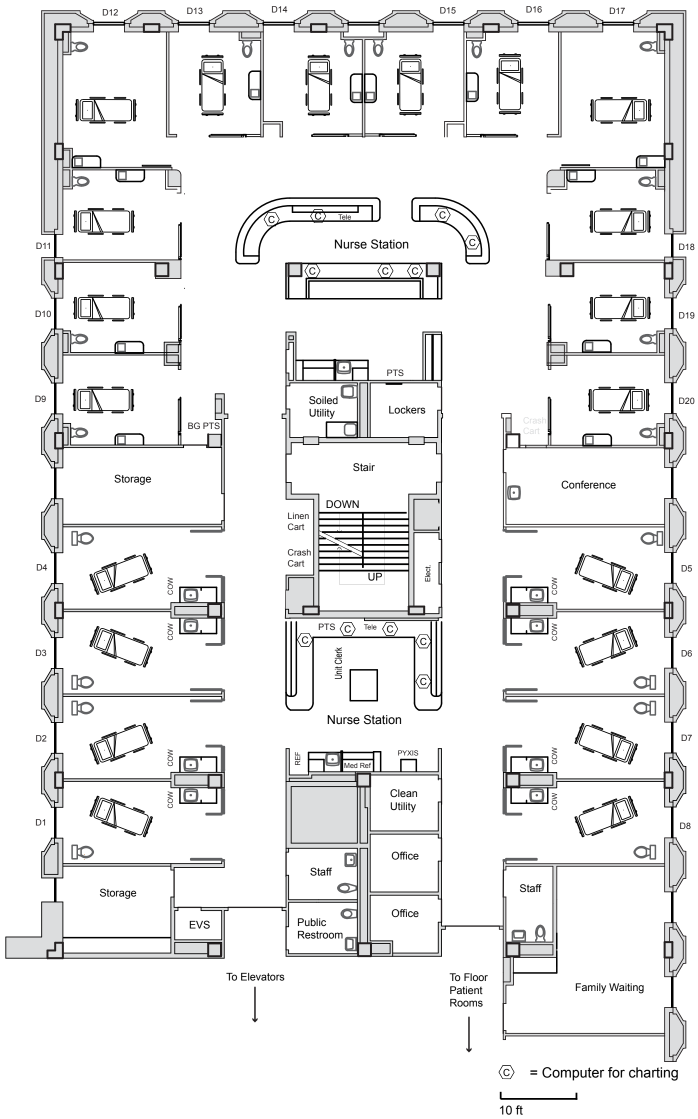


Figure 4.10. ICU D, Emory Midtown Hospital. Note that the only visual opening shown to each patient room is the open door.

4.3.3 Outcome Measurements

ICU mortality, defined as death occurring on an ICU day, was the outcome of interest.

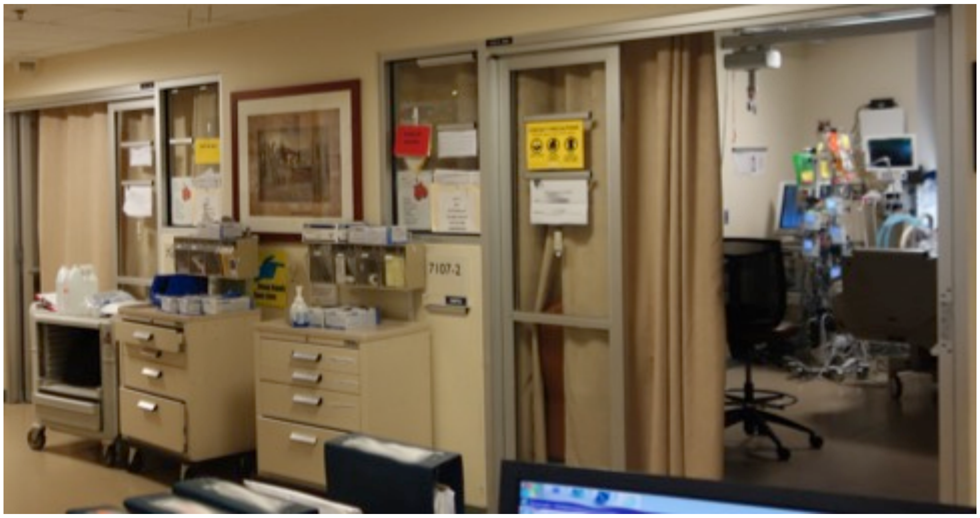


Figure 4.11. Double Corridor section, View of Rooms D1-D2. Note placement of visual information displays on small windows and curtains drawn to breakaway door. Also note example of distributed supplies.

Figure 4.12. U-Shaped section, View of Rooms D16-D17. Note placement of visual information displays and curtains drawn to breakaway door. Also note example of distributed supplies.

4.3.4 Primary Exposure Variable

The primary exposure variable was isovist connectivity. The floor plan for each unit (in AutoCAD) was verified against the actual units in use. Because the majority of the windows to the interior of the units were either permanently obstructed by affixed whiteboards or usually obstructed with curtains, information displays, and/or supply cabinets, all the study units were analyzed as if the only view was through the open door, **Figures 4.5-12.** Choosing to assess visual graph measures with doors/windows open or closed is standard practice in spatial analysis; in this case, doing so assesses each room in a uniformly restricted condition. Using Depthmap UCL (Turner, 1998), a spatial analysis software developed at University College London, we first overlaid a grid of vantage points upon the layout broken only by visual barriers. We then generated the isovist from each head of bed (4 ft^2) using the step depth metric. Used purely for ease of computation, step depth ≤ 1 approximates the isovist by 'selecting' all the points within the HOB isovist (step depth = 1), including the actual HOB (step depth = 0)**, Figure 4.13**. Using the same software, we generated connectivity scores by calculating the number of points directly connected to a point in question (via an imaginary straight line), without a change in direction, **Figure 4.14 and 4.15.** For each HOB isovist (selected as step depth ≤ 1), we averaged the connectivity values of every point (represented as a tile centroid) in each respective isovist, resulting in an isovist connectivity (IC) score for each patient room, **Table 4.1; Figure 4.16.** The raw IC scores formed the basis of all spatial analysis; that is, scores were not relativized by unit size.

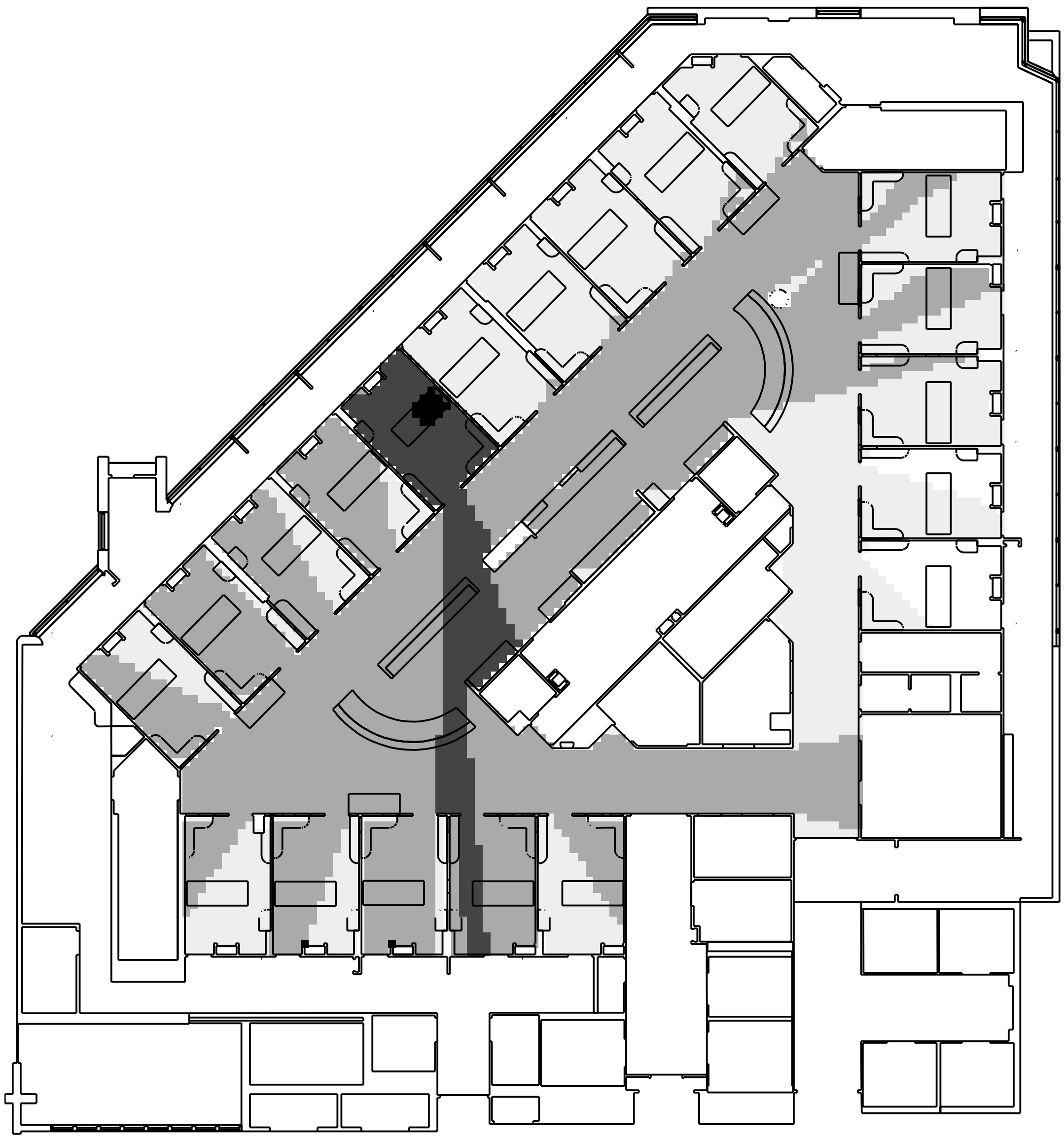
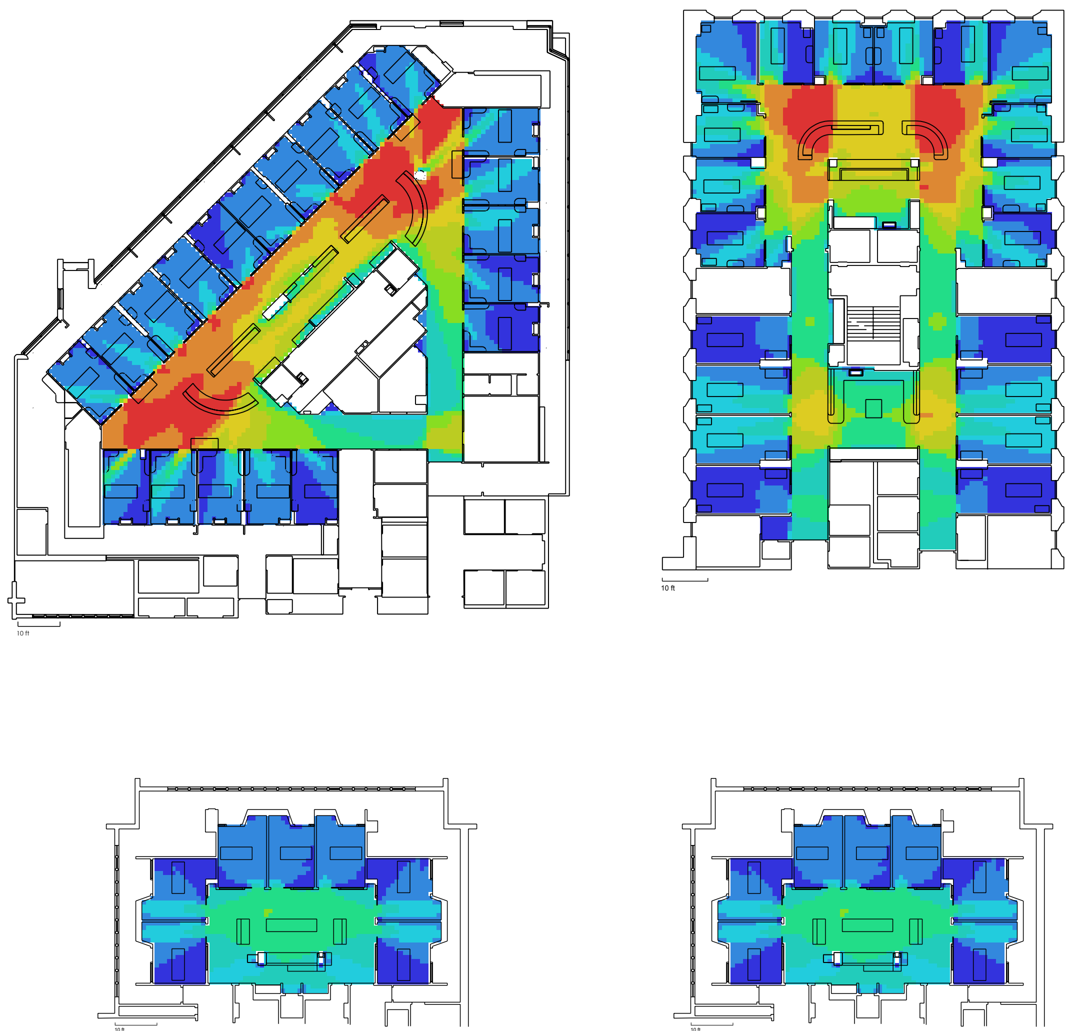


Figure 4.13. Step depth (SD) Graph, Room A11. 'Black' tile centroids (SD=0) are the selected head of bed tile centroids. 'Dark Gray' tile centroids (SD=1) are mutually visible to the set of selected tile centroids, in this case, the head of bed (SD=0); 'Medium gray' tile centroids (SD = 2) are 1 turn away from mutual visibility; 'Light Gray tile centroids (SD = 3) are 2 turns away from mutual visibility.

ICU A | ICU D



ICU B | ICU C

Figure 4.14 Connectivity Graph, Depthmap UCL. Red areas reflect greatest connectivity; dark blue areas reflect least connectivity.

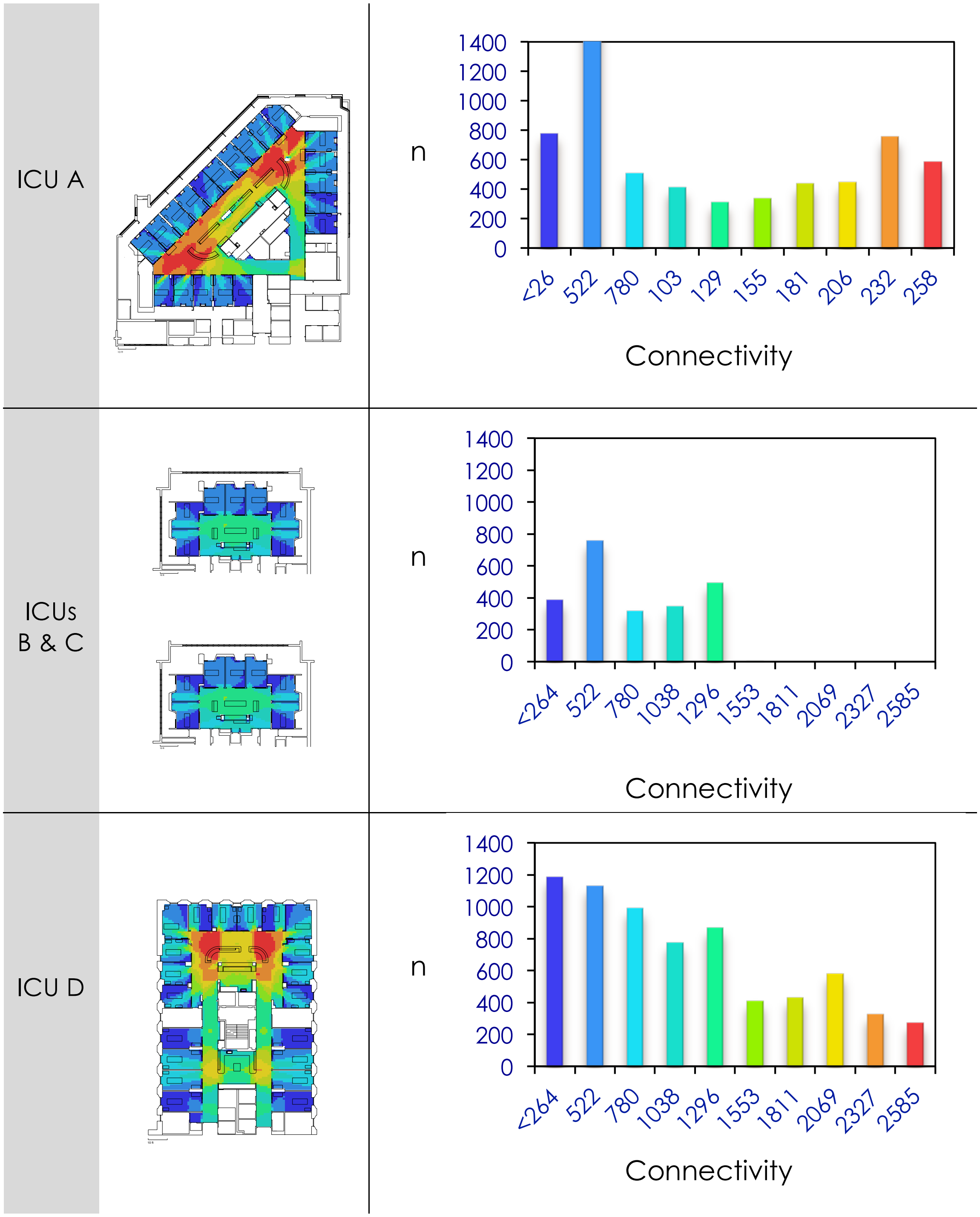


Figure 14.15 Distribution of connectivity scores by floor plan; colors correspond directly. Because connectivity was generated from 1-ft^2 tiles, connectivity scores also correspond to square footage. For example, ICU A has 1,340 ft^2 of highly connected (red/orange) space; ICU D has 596 ft^2 of highly connected space.

Table 4.1 Isovist Connectivity Scores by Room

Room	Isovist Connectivity Score	Room	Isovist Connectivity Score
A1	612.93	C1	518.03
A2	1254.96	C2	556
A3	1315.79	C3	739.71
A4	1715.30	C4	691.83
A5	1793.85	C5	746.35
A6	1331.10	C6	557.77
A7	1350.99	C7	517.65
A8	1243.68	D1	425.07
A9	1283.82	D2	1117.92
A10	1201.00	D3	1103.40
A11	1071.43	D4	475.10
A12	1307.32	D5	460.32
A13	1329.56	D6	1099.89
A14	1340.66	D7	1118.31
A15	1387.10	D8	425.93
A16	1781.54	D9	1256.15
A17	1858.72	D10	1640.93
A18	1099.74	D11	1739.11
A19	1300.50	D12	1588.77
A20	1089.94	D13	1340.51
B1	518.03	D14	1428.03
B2	556	D15	1431.18
B3	739.71	D16	1332.51
B4	691.83	D17	1579.53
B5	746.35	D18	1741.16
B6	557.77	D19	1659.97
B7	517.65	D20	1289.90

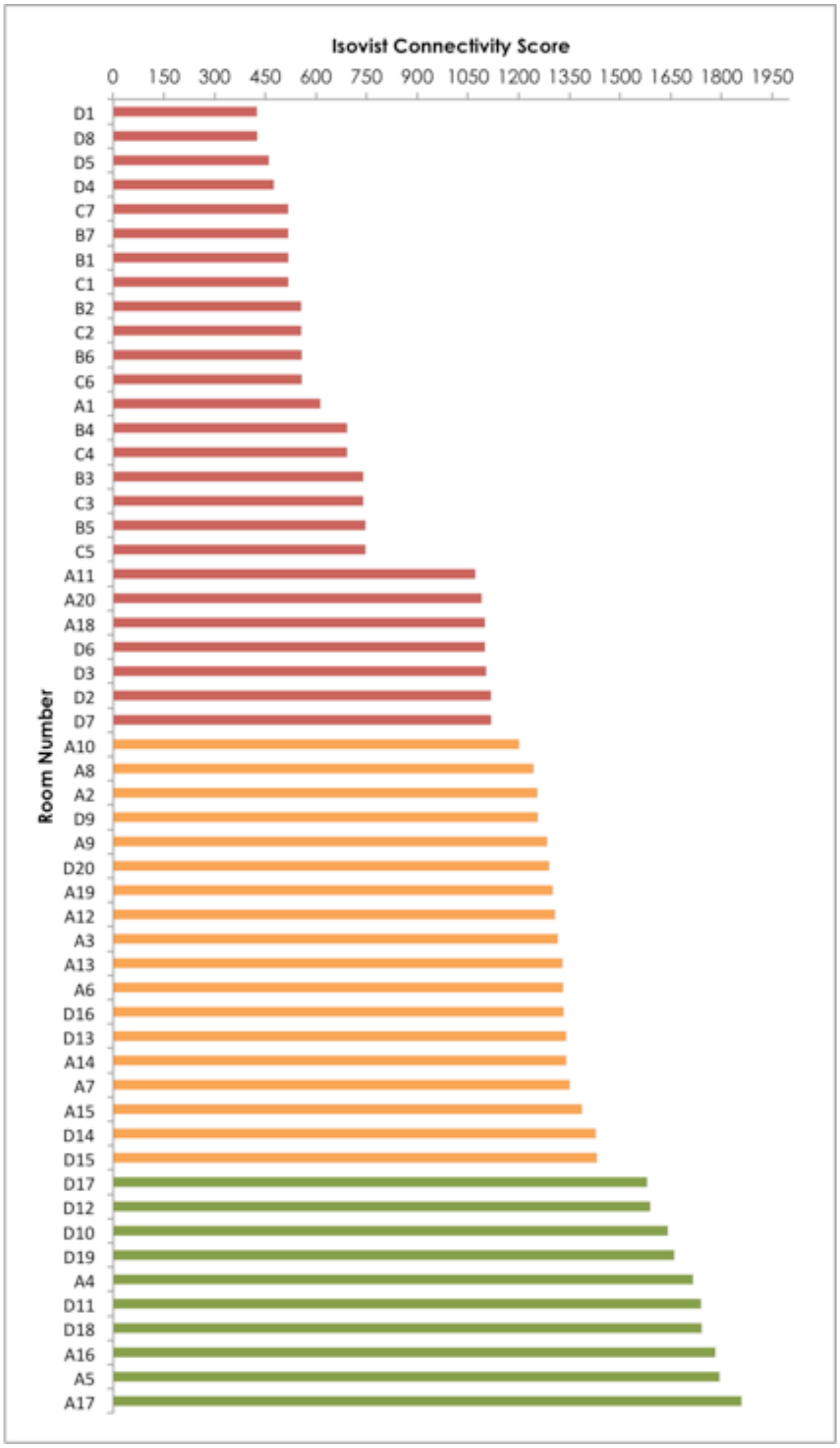


Figure 4.16 Isovist Connectivity Score by Room. Visibility Groups Low (Red), Medium (Orange), and High (Green).

4.3.5 Covariates

In addition to age, sex, and ventilation days, we used clinically derived acute and chronic illness severity adjustment metrics - Sepsis-related Organ Failure Assessment (SOFA) scores day 1, and Charlson Comorbidity Index (CCI) scores.

4.3.6 Statistics/Analysis

Data for all were extracted from the electronic medical records for all eligible patients. Isovist connectivity values are reported as raw scores by patient room. We formed visibility groups from IC values using hierarchical clustering, Ward method, **Figure 4.17, Table 4.2.** All categorical variables are reported as counts with percentages. Skewed continuous variables, as determined by the Shapiro-Wilk test, are reported as median and interquartile range (25-75 percentiles). Normally distributed continuous variables are reported as means with standard deviation. Unadjusted comparisons of descriptive statistics and outcomes were calculated using Pearson correlation (categorical) or Kruskal-Wallis test (continuous non-normal), with $p \leq 0.05$ considered significant one-way analysis of variance. Dunn Method with Control for comparisons between groups as required.

For the binary outcome variable ICU mortality, we performed a multivariate logistic regression analysis to assess the association between IC and ICU mortality, adjusting for age, sex, ventilation days, Charleson Comorbidity Index (CCI), and Sepsis-related Organ Failure Assessment (SOFA) day 1. The adjusted odds ratio (OR) with 95% CI is reported. Effects with a probability of less than 0.05 were considered significant.

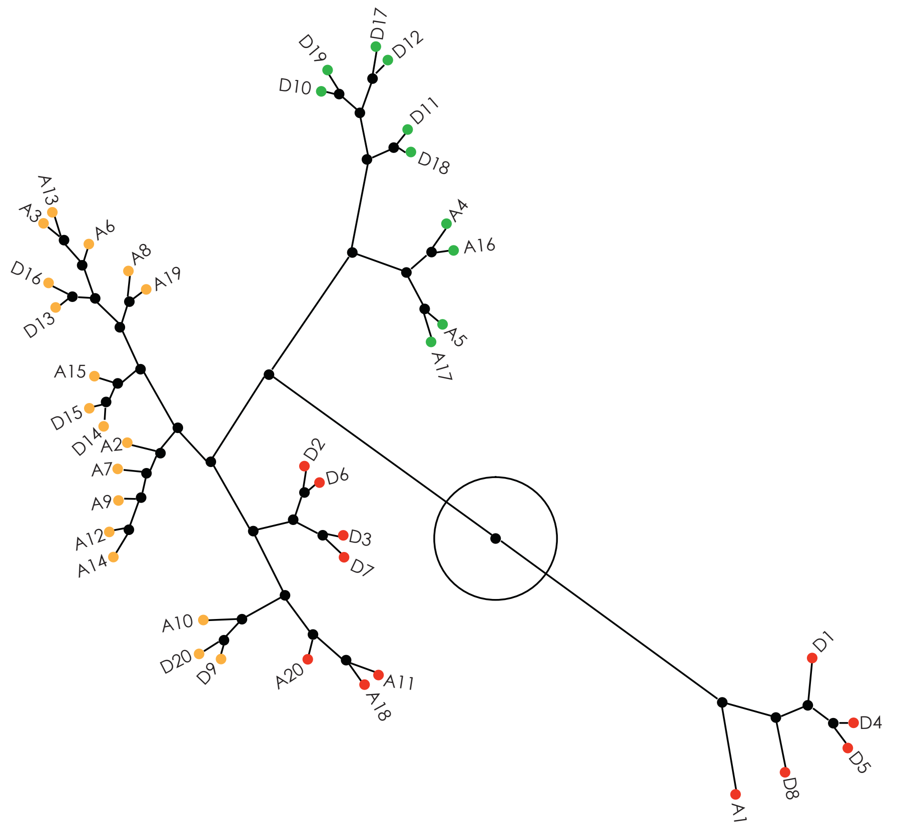


Figure 4.17 Hierarchical clustering, Ward method. ICUs B and C were removed from the graphic for clarity. All rooms in ICUs B and C clustered in the Red, lowest visibility group.

Table 4.2 Distribution of Rooms by Isovist Connectivity group within each ICU.

UNIT	Isovist Connectivity Group		
	LOW VIS	MED VIS	HIGH VIS
ICU A (n)	4	12	4
ICUs B & C (n)	14	0	0
ICU D (n)	8	6	4

Logistic regression analyses were performed in Stata 13 SE (StataCorp, College Station, TX); all other analyses were performed in JMP®, Version *12* (SAS Institute Inc., Cary, NC, 1989-2016). This study was approved by the Emory and Georgia Institute of Technology Institutional Review Board.

4.4 Results

4.4.1 Patient Characteristics

We examined a total number of 1519 patient records; 1385 (91%) were eligible for inclusion, **Table 4.3.** Using hierarchical clustering, we created visibility groups according to patient assignment to a low (n=877), medium (n=311), or high (n=197) raw IC score room, **Figure 4.16 and 4.18.** Patient demographic characteristics and acute illness severity (SOFA day 1 score) were similar across groups. Chronic comorbidity scores (CCI) were significantly higher in the medium visibility group compared to the low visibility group (p=0.024); there were no other significant differences. ICU length of stay was statistically higher in the high visibility group compared to the low visibility group (p=0.005), but not clinically significant; there were no other significant differences. **Appendix A** reports the unadjusted characteristics and outcomes for each of the 4 ICUs.

Table 4.3 Sample Characteristics

Characteristics	Overall (N=1385)	LOW VIS (n=877)	MED VIS (n=311)	HIGH VIS (n=197)
Demographics				
Age, median, IQR	64 (52-75)	64 (52-75)	61 (52-72)	64 (54-75)
Female, %	49.2%	47.0%	54.7%	50.8%
Severity of Illness				
SOFA Day 1, median, IQR	7 (4-11)	4 (2-7)	4 (2.2-7)	4 (3-7)
CCI, median, IQR	5 (3-7)	4 (2-7)[a]	5 (3-7)[a]	5 (3-7)
ICU LOS, median, IQR	3 (2-5)	3 (1-5)[b]	3 (2-5)	3 (2-7)[b]

[a]*p*<0.05 between medium and low visibility groups.

[b]*p*<0.01 between high and low visibility groups.

4.4.2 Patient Outcomes

The unadjusted mortality was 14.5% for the entire cohort. Unadjusted mortality for low, medium, and high visibility rooms were 15.7%, 13.8%, and 10.2%, respectively. The change in mortality by room visibility did not achieve statistical significance (p=0.123). Adjusted estimates demonstrated an independent association between IC and ICU mortality. Patients exposed to a high IC score room experienced a 42% (95% CI, 0.33-0.99) lower odds of death compared to patients exposed to a low IC score room, p=0.048. Patients in medium visibility rooms trended similarly, but did not achieve statistical significance, **Table 4.4**. **Appendix B** reports hospital discharge disposition by visibility group.

ICU A | ICU D

ICU B | ICU C

Figure 4.18 Isovist Connectivity Group by Unit

Table 4.4 Comparison of Adjusted Relationship between IC and ICU Mortality compared to referent group, Low Visibility.

Outcome Variable	ICU MORTALITY	
	OR (95% CI)	*p*
Patient Age at Visit	1.00 (0.99-1.01)	0.62
Male (vs. Female)	0.81 (0.58-1.11)	0.18
SOFA score day 1	1.17 (1.12-1.22)	<0.01
CCI	1.05 (0.99-1.10)	0.07
Ventilation days	1.03 (0.99-1.06)	0.08
High vs. Low Visibility[a]	0.58 (0.33-0.99)	<0.05
Med vs. Low Visibility[a]	0.76 (0.52-1.11)	.16

[a]Adjusted for Charlson Comorbidity Index score, Sequential Organ Failure Assessment score day 1, age, sex, and ventilation days.

4.5 Discussion

Efforts to improve the structure and process of sepsis care are vital given the tremendous associated social, organizational, and financial burdens. Advances in our understanding regarding the significance of clinician training and presence (structure), nurse-patient ratios (structure), and standardized approaches to care (process, e.g. bundles, checklists, protocols) are improving patient outcomes however slowly. We present a novel approach to assess a structure component (unit design) of sepsis care that was significantly associated with ICU mortality rates. Furthermore, the magnitude was substantial; patients exposed to rooms with high levels of concurrent patient HOB and unit visibility experienced 42% lower odds of death compared with patients exposed to low levels. Our findings confirm previous research associating patient visibility and mortality; moreover, we provide visibility metrics that supersede intuited, 'designed' visibility.

Patient visibility is a primary consideration in ICU design; the latest SCCM guidelines (2012) recommend 'direct visualization', achieved by HOB visibility to the main work area or main ICU corridor. We demonstrate the benefit of HOB visibility but also reveal the insufficiency of generic visibility to 'main locations'. Indeed, all patient rooms in our sample conform to these requirements and yet the entirety of ICUs B and C and subsections of ICUs A and D differed empirically and sufficiently to be associated with comparatively higher odds of patient death.

Isovist connectivity was conceptualized by a deep understanding of both clinician work and architectural design process and as such, reflects the requirements of both fields. First, the isovist embodies clinician need for patient observation and supervision. Several authors conceptualize patient surveillance behaviors and activities (process)(Dresser, 2012; Kelly & Vincent, 2011); all require structure within which to operate. Second, the connectivity measure reflects clinician need to receive and provide inter/intra professional support, a general awareness of others, and moreover, is associated with probabilistic movement.

The last requirements attend to design. Isovist connectivity (1) can be assessed with 2D drawings prior to any construction and can be used iteratively, (2) is robust to unit configuration, work areas, and number of beds, and (3) supersedes intuition. Certain low visibility rooms are naturally apparent, e.g. A1 and A20; indeed, ICU staff in Units A and D anecdotally verify this notion. Consistent among the obviously poor rooms was a lack of patient visibility; these rooms often faced a corridor (with no view to work areas), confirming previous studies (Leaf et al., 2010; Lu et al., 2014). In this sample, however, we found rooms that were silently poor. Several authors of this paper were privileged to work as clinicians in the study units. We were astounded to find that ICUs B, C, and sections of Unit D were among the worst spatially performing; we enjoyed the approximation to a Nightingale ward, i.e. patients and colleagues visible and audible. In terms of architectural requirements, all of the rooms in ICUs B and C had direct connections with corridors and central stations as did the 'double corridor' half of Unit D.

Returning to Donabedian's structure-process-outcome model, however, we recognize that space is not inherently active; people activate space through society, culture, and movement. We do not have counts for 'the presence of people' for this study, but studies in intensive care units reveal a preference to linger and move in spaces that provide greater awareness and the opportunity for interaction (Cai & Zimring, 2012; Rashid, Boyle, & Crosser, 2014). Units B and C had low connectivity values relative to the larger ICUs A and D; indeed, they had fewer total tiles. It is critical to recall that by the procedure described in Section 4.3.4, the IC score was not relativized for unit size. This was by design; it may be that larger units (supporting more patients and therefore more clinicians) have higher clinician density (staff and consulting services) and a longer clinician length of stay due to the volume of patients on their service in those units. Indeed, we found a statistically significant relationship between high non-relativized IC scores and ICU patient mortality. We acknowledge, however, that the mechanism is unclear. Further research will provide greater understanding as to the mechanism and therefore, the design implications, e.g. minimum safe IC affordances, density and position of people or directional tendencies. In the case of ICU D, the difference between the U-shaped and double-corridor sides may be the availability of information (more spaces potentially occupied by people) and may also be related to a sense of crowding; the U-shaped portion is comparatively more convex. Future study should consider the relationship between patient outcomes and relativized IC scores, percent of available area versus absolute scores and also as a percent of highest scores, and perhaps most importantly, investigate the mechanism.

This study has considerable strengths. Only 2 studies (using the same population) have directly studied the impact of patient visibility on ICU patient mortality; this study is the first to use rigorous spatial measures reflecting the potential for both patient observation and organizational awareness from all potentially occupied space. The spatial configurations (U-shape, double-corridor, and triangular) reflect various ICU types and enabled us to test spatial effect with a single, cross-configurational measure prior to construction. Finally, this study is one of the few environment-behavior studies to control for patient acuity.

This study has potential limitations. First, there is a risk of non-equivalence between individual units and visibility groups, particularly as the sample spans two hospitals. This potential limitation also supports generalizability, however, showing persistence across unit configuration, type, and staffing. There is also the risk of non-equivalence between units and visibility groups insofar as patient type and acuity over a 2.5 year study period, even within a sepsis subgroup. We attempted to account for these differences by adjusting for acuity and comorbid factors, but nevertheless, we acknowledge the potential for differential outcomes across patient types.

We evaluated unit particularities with a sensitivity analysis, excluding ICUs B and C (all rooms were in the same visibility category), for inter-unit variation. Although not reaching statistical significance, (likely due to sample size), the logistic regression revealed similar trends as reported here for the primary outcome. Future studies should attempt to match patients by primary diagnosis or by type, e.g. surgical, medical, and transplant. These studies should also consider the potential effect of windows – a view to the outside. Although ICU D had windows in all rooms, the room widths required that patients face the interior of the unit (providing natural light but no view), with the exception of D12 and D17. No rooms in ICU A had views to the outside. Replication studies with additional ICU configurations and exterior glazing, unit types, and patients are necessary.

Second, we were not able to evaluate the impact of clinician staffing. There may be differential nurse-patient assignments according to years of experience, skill and knowledge level, and the available nursing pool. There may be medical staff differences by training, quality, or behavior. We were also not able to account for nursing or physician/advanced practice provider (APP) presence; the effect of the built environment may be hidden in clinicians' effort to overcome structural obstacles through self-regulation according to patient need, sacrificing broader organizational goals for the good of the patient. Future studies should account for a cumulative nurse effect per patient, as well as clinician behaviors with corresponding mapping samples.

Third, we did not have access to long-term outcomes, e.g. 30-60 day mortality, and so cannot assess the long-term implications of visibility; future study should also account for these outcomes. While outcomes such as hospital or long-term acute care mortality may provide a longer view however, these outcomes are likely clouded by those events occurring outside the ICU. It is also possible that differential mortality across visibility groups is a function of hospice disposition, rather than any effect of visibility. We view this possibility as unlikely, given the similar distributions across the sample, **Appendix B.** We fully acknowledge, however, that ICU mortality is a rather blunt outcome; future work should look at more intermediary steps, e.g. supportive care failures, if our interest lies in the events that occur in the ICU.

Fourth, we limited the patient sample to sepsis only, which may limit the generalizability to other ICU types, e.g. neurosurgical. Sepsis treatment is labor intensive and time sensitive; these results may not replicate in SICUs where the outcomes are more dependent upon events in the operating room (surgical sepsis patients notwithstanding). Sepsis is however, increasing in incidence and estimated to be a leading cause of morbidity and mortality worldwide (M. Singer et al., 2016). Given these implications, future study should continue to include sepsis patients to improve care and survival, while also expanding to other patient types.

Finally, these study ICUs are part of a single academic health system with standardized care protocols, which may limit the generalizability. That being said, our findings provide critical insight into the measureable effects of the built environment on patient outcomes. Future studies should expand to a variety of other health systems to assess for impact and significance.

The intensive care unit design process is complicated by physical (existing building and structure), regulatory (design and construction guidelines), budgetary, and organizational (people, process, and culture) constraints. The tension between precedent, personal expertise, and evidence in architectural and interiors design is ever increasing, founded in the 'evidence-based design' movement. Methods and metrics to create an evidence base are expanding, drawing from environmental psychology, human factors, ergonomics, and nursing, while largely focused on a resulting process, e.g. time at the bedside.

This is not a fault; process is an intermediary step toward affecting outcome. This study creates a precise link to clinical outcomes – the raison d'etre.

4.6 Conclusions

Together with our clinical and academic partners, the field of evidence-based design is transitioning to the science of healthcare delivery. Our study builds upon existing evidence linking visibility as an independent risk factor over and above patient characteristics. Moreover, we improve the future evidence base by providing a precise, iterative, and cross-configurational measure that is grounded in a deep understanding of clinician behaviors. Testing for isovist connectivity during the design process and in existing ICUs may lead to ICUs that better support patient and organizational outcomes.

CHAPTER 5

CONCLUSIONS

Summary of Findings

The built environment occupies a fundamental role, underlying all processes and organizational efforts. Reason views this latent condition as designed, originating in strategic decisions that 'unlike active failures … can be identified and remedied before an adverse event occurs', (2000). The notion of preventability is rooted in classification however, much as with 'disease' and now 'adverse events' (C. Vincent & Amalberti, 2015). Lacking rigorous visibility measurement, we relied upon broad identifiers and intuition. As measurement is developed and the perimeter of safety expands, 'primum non nocere', should move beyond the process of care and operational and organizational capabilities to include the built environment. Indeed, the primary intent of this dissertation study is to identify and codify that which was anecdotal, to soon prevent and provide a remedy for poor visibility.

In Chapter 2 we demonstrated (1) an inverse trend between patient visibility and ICU mortality for the sickest of patients and (2) the potential for no effect at a medium visibility level. We discussed the limitations in currently available visibility metrics and methods, especially related to differing architectural configurations and spatial selection. That we might operationally match visibility measures with worker behavior, we identified the need to (a) account for all potentially worker-occupied space, (b) account for patient head or head of bed primacy, (c) be robust across configurations, and (d) be robust to distance. We conceptualized ranges of visibility affordances, lobbying for analysis by visibility group. Lastly, we argued that before linking spatial characteristics to patient outcomes, we must have operationally sound visibility measures.

In Chapter 3, we demonstrated the conceptual development of a new spatial variable, isovist connectivity, through a discussion on the predictive value of spatial variables on locational preferences in a myriad of settings, including clinician movement. Healthcare environments are similar to other settings with one caveat: patient observation is a critical and essential job function. We seek to capture this complex visual condition with isovist connectivity, as an environment that affords both patient observation and visual access may impact patient safety. Isovist connectivity of a region, such as square marking the head of a patient bed, therefore, provides a measure of the quality of visual access to the entire layout available to anyone who is at the same time keeping the head of the bed in surveillance. Higher isovist connectivity values associated with a region should allow a person to visually survey larger areas of the nursing floor while monitoring a patient, and allow him or her better organizational awareness. In theory, therefore, higher isovist connectivity of a region should correspond with better patient outcomes.

In Chapter 4, we tested a new cross-configurational measure for risk assessment that accounts for all potentially occupied space and head of bed primacy, demonstrating concurrent patient visibility and visual access as an independent risk factor over and above patient characteristics. Moreover, we found that simultaneous patient and organizational visibility is not intuitively apparent, e.g. heads visible to the team station or hallway. Testing for isovist connectivity during the design process and in existing ICUs may lead to ICUs that better support patient and organizational outcomes. It is likely that the mechanism of patient survival as predicted by isovist connectivity is the presence of people. Rooms with highly connected isovist polygons may experience higher clinician density thereby conferring decreased risk. It was beyond the scope of this dissertation to fully explore the relationship between isovist connectivity and the density of people, but that necessity is acknowledged as a next step.

5.2 Current Direction

While more investigation is necessary, the immediate clinical and design implications are considerable. Given that an IC analysis is relatively rapid and inexpensive to conduct, we advise that those in active ICU design phases consider running this analysis for latently poor IC rooms. Revealing these rooms prior to construction may allow designers and clinicians to uncover potential causes and corresponding design and process solutions, e.g. HOB direction, headwall position, corridor angles, workstation layouts and distribution, patient assignments, and other process measures.

For existing ICUs, an IC analysis may illuminate an underlying spatial deficiency (potentially confirmed by clinician suspicion) about a particular room or set of rooms. The ability to closely examine these working rooms may provide both insight into the mechanism and resulting process and design tensions. Removing whiteboards will improve patient visibility but another solution will be needed for persistent group communication. Maintaining open curtains will also improve patient visibility but may impact perceived privacy. Desired architectural changes may be unwieldy or too costly, and might be approximated with environmental affordances (workstations and chairs) and of course, supportive process and culture. Given the currently available measurement and evidence, we posit that the goal for existing ICUs and those in design is management and prevention.

5.3 Future Direction

The intensive care unit design process is complicated by physical (existing building and structure), regulatory (design and construction guidelines), budgetary, and organizational (people, process, and culture) constraints. The tension between precedent, personal expertise, and evidence in architectural and interiors design is ever increasing, founded in the 'evidence-based design' (EBD) movement. Ahead of EBD practitioners, clinician researchers are expanding the boundaries of 'primum non nocere'; the scope of preventable adverse events is changing as what was once seen as good enough or unavoidable is no longer acceptable (C. Vincent & Amalberti, 2015).

As the notion of duty changes, therefore, we can imagine a parallel change in potential responsibility and opportunity. Are architects liable/compensated on the basis of designing for patient safety? Knowing which rooms are poorly visible, can ICU teams develop strategies to mitigate this visibility risk? Certainly, more study is required before such measures would reasonably take place, and future ICU design could embark upon spatial analysis iteration preventatively.

There are thousands of ICUs, emergency departments, and general care wards across the United States, however, with existing visibility affordances and without the opportunity or budget to reimagine their visibility milieu. Additional study is required to explore risk mitigation for poor rooms through the use of policy, technology (electronic-ICU), or changes to the built environment.

Through partnerships between clinical, academic, and design stakeholders, we are transitioning to the science of healthcare delivery, as tackling patient safety requires engagement of the entire health system—the people, the processes, the policies and the environment of care.

Appendix A

Unit Characteristics and Clinical Outcomes

Characteristics	Overall (N=1385)	ICU A (n=253)	ICU B (n=282)	ICU C (N=322)	ICU D (n=528)	P Value
Demographics						
Age, y, mean (SD)	62.1 (17.0)	57.4 (15.7)	63.7 (17.0)	59.7 (18.4)	64.9 (16.1)	<0.0001*[7]
Female, %	49.2%	49.4%	43.60%	48.10%	52.8%	0.09
Severity of Illness						
SOFA, Day 1, mean (SD)	7.5 (4.5)	8.0 (4.8)	7.8 (4.6)	7.2 (4.7)	7.4 (4.1)	0.12
CCI, mean (SD)	5.0 (3.2)	5.0 (2.7)	4.8 (3.2)	4.4 (3.3)	5.6 (3.3)	<0.0001*[8]
Clinical Outcomes						
Ventilator Days, mean (SD)	6.2 (5.0)	5.3 (4.3)	6.3 (4.2)	5.5 (3.7)	7.0 (6.2)	0.0124*[9]
ICU LOS, median (IQR)	3 (2-5)	3 (2-5)	2 (1-4)	2 (1-5)	3 (2-6)	0.0005*[10]
ICU Survival No. (%)	1184/1385 (85.5)	218/253 (86.2)	245/282 (86.9)	266/322 (82.6)	455/528 (86.2)	0.45

SOFA, Day 1= Sepsis-related Organ Failure Assessment; CCI = Charlson Comorbidity Index; LOS= Length of Stay. SD = Standard Deviation.

[7] Mean age for ICU D patients is significantly higher than for ICU A (p<0.0001) and ICU C (p<0.0001). Mean age for ICU B patients is significantly higher than ICU A (p=0.0001) and ICU C (p=0.019) mean patient age.

[8] Mean CCI scores for ICU D patients are significantly higher than ICU B (p<0.0001) and ICU C (p=0.007) patients, though not for ICU A patients.

[9] Mean vent days for ICU D are significantly higher than ICU A (p=0.024) and ICU C (p=0.050). No other differences are significant.

[10] Mean ICU LOS is significantly higher for ICU D than for ICU B (p=0.033)and ICU C (p=0.0004). No other differences are significant.

Appendix B

Hospital Disposition by Visibility Group

Hospital Disposition	Overall (N=1385)	LOW VIS (n=877)	MED VIS (n=311)	HIGH VIS (n=197)
Home Self Care, n (%)	283 (20.4)	170 (19.4)	67 (21.5)	46 (23.4)
Home Health, n (%)	229 (16.5)	140 (16.0)	60 (19.3)	29 (14.7)
Hospice-Home, n (%)	38 (2.7)	24 (2.7)	9 (2.9)	5 (2.5)
Hospice, Medical Facility, n (%)	257 (18.6)	168 (19.2)	53 (17.0)	36 (18.3)
Intermediary Care Facility, n (%)	1 (0.1)	1 (0.11)	0 (0)	0 (0)
Long Term Care Hospital, n (%)	45 (3.2)	24 (2.7)	15 (4.8)	6 (3.0)
Short Term Care Hospital, n (%)	15 (1.1)	11 (1.3)	1 (0.32)	3 (1.5)
Other rehab Facility, n (%)	27 (1.9)	21 (2.4)	3 (0.96)	3 (1.52)
Skilled Nursing Facility, n (%)	210 (15.2)	128 (14.6)	42 (13.5)	40 (20.3)
Expired, n (%)	268 (19.4)	183 (20.9)	57 (18.3)	28 (14.2)
Other, n (%)	12 (0.9)	7(0.8)	4 (1.29)	1 (0.5)

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